Modeling, Analysis and Design of Synchronous Buck Converter Using State Space Averaging Technique for PV Energy System.

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MODELING, ANALYSIS AND DESIGN OF SYNCHRONOUS BUCK CONVERTER USING STATE SPACE AVERTAGING TECHNIQUE FOR PV ENERGY SYSTEM

A Thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology in "Electrical Engineering"

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CERTIFICATE

This is to certify that the draft report/thesis titled "**Modeling, Analysis and Design of Synchronous Buck Converter Using State Space Averaging Technique for PV Energy System**", submitted to the National Institute of Technology, Rourkela by **Gunda Suman (Roll. No. 109ee0519), B.V.S Pavan Kumar (Roll. No. 109ee0518) and M Sagar Kumar (Roll. No. 109ee0153)** for the award of **Bachelor of Technology** in Electrical Engineering, is a bonafide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements.
The draft report/thesis which is based on candidate's own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the draft report/thesis is of standard required for the award of a **Bachelor of Technology** in Electrical Engineering.

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Dedicated to,

Our Parents & friends who has been there for us from genesis to apocalypse…

ABSTRACT

If we start forecasting in the view of electrical energy generation, in the upcoming decade all the fossil fuels are going to be extinct or the worst they are going to be unaffordable to a person living in typical circumstances, so renewable power energy generation systems are going to make a big deal out of that. It is extremely important to generate and convert the renewable energy with maximum efficiency. In this project, first we study the characteristics of low power PV array under different values of irradiance and temperature. And then we present the exquisite design of Synchronous Buck Converter with the application of State Space Modeling to implement precise control design for the converter by the help of MATLAB/Simulink. The Synchronous Buck Converter thus designed is used for portable appliances such as mobiles, laptops, iPod's etc. But in this project our main intention is to interface the PV array with the Synchronous Buck Converter we designed, and we will depict that our converter is more efficient than the conventional buck converter in terms of maintaining constant output voltage, overall converter efficiency etc. And then we show that the output voltage is maintaining constant irrespective of fluctuations in load and source. And finally we see the performance of Synchronous Buck Converter, which is interfaced with PV array having the practical variations in temperature and irradiance will also maintain a constant output voltage throughout the response. All simulations are carried under MATLAB/Simulink environment.

And at last experimental work is carried out for both conventional buck converter and also for synchronous buck converter, in which we observe the desired outputs obtained in simulations.

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ABBREVIATIONS AND ACRONYMS

MNRE	-	Ministry of New and Renewable Energy
IREDA	-	Indian Renewable Energy Development Agency
PVA	-	Photo Voltaic Array
AC	-	Alternating Current
DC	-	Direct Current
SPV	-	Solar Photo Voltaic
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
PWM	-	Pulse Width Modulation
EMI	-	Electro Magnetic Interference
MATLAB	-	MATrixLABoratory
MPPT	-	Maximum Power Point Tracking
PID	-	Proportional, Integral and Derivative
IC	-	Integrated Circuit
LED	-	Light Emitting Diode
SMPS	-	Switched Mode Power Supply

CHAPTER **1**

Introduction

1.1 MOTIVATION:

As the days go by, the demand of power is increasing gradually and on the contrary the resources used for power generation are becoming inadequate. Apart from the reason of inadequate resources, the methods used for power generation by fossil fuels are not even environment friendly and they devote an ultimate reason for global warming and greenhouse effect.

So it is the time to initiate the usage of renewable energy resources on very large scale. The three main available renewable energy resources are (i) Direct Solar Energy, (ii) Hydro Energy and (iii) Wind Energy. Hydro Energy generation and Wind Energy generation are of course two of the main sources of renewable energies, but the main disadvantage in Hydro Energy is that, it is seasonal dependent and in Wind energy is that it is geographical location dependent [1]. On the other hand Solar Energy is prevalent all over the globe and all the time. The amount of irradiance and temperature may vary from place to place and from time to time but under given conditions Solar Energy system can be implemented. Solar Energy or PV energy system is the most direct way to convert the solar radiation into electricity based on photovoltaic effect. Despite of high initial costs, they are already have been implemented in many rural areas. In future the cost of the PV panel also may diminish, because of the advancing technology and also the competition between manufacturers. And therefore, the time is not so far that almost every middle class person can afford his own solar panel at home for at least some basic requirements.

In the perspective of above noted points, it is evident that PV Energy plays a pioneer role in the forthcoming future. So, it is our duty to learn, implement and improvise the idea as fast as we can, so that it becomes prevalent rather than precarious to the future generations.

1.2 PV ENERGY:

1.2.1 Photovoltaics (PV):

Photovoltaics are best known as a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons. The photovoltaic effect refers to photons of light exciting electrons into a higher state of energy, allowing them to act as charge carriers for an electric current. The photovoltaic effect was first observed by Alexandre-Edmond Becquerel in 1839.The term photovoltaic denotes the unbiased operating mode of a photodiode in which current through the device is entirely due to the transduced light energy. Virtually all photovoltaic devices are some type of photodiode.

Solar cells produce direct current electricity from sun light which can be used to power equipment or to recharge a battery. The first practical application of photovoltaic was to power orbiting satellites and other spacecraft, but today the majority of photovoltaic modules are used for grid connected power generation. In this case an inverter is required to convert the DC to AC. There is a smaller market for off-grid power for remote dwellings, boats, recreational vehicles, electric cars, roadside emergency telephones, remote sensing, and cathodic protection of pipelines.

Cells require protection from the environment and are usually packaged tightly behind a glass sheet. When more power is required than a single cell can deliver, cells are electrically connected together to form photovoltaic modules, or solar panels. A single module is enough to power an emergency telephone, but for a house or a power plant the modules must be arranged in multiples as arrays.

1.2.2 PV Energy Efficiency:

The output voltage thus obtained from the PV panel is DC. For low power applications, dc-dc converters are employed to step-up or step-down the output DC voltage according to the load requirements. However overall conversion efficiency is very low (typically 6.5 percent). So accurate modeling and design of dc-dc converter is necessary in order to improve the overall system performance with cost effective solution [2].

As the efficiency of solar panel itself is very less and it is inevitable, so the precaution should be taken such that the efficiency of the converter should be maximum. For the efficient regulation of output DC voltage, Synchronous Buck Converter is designed in the project. Various converter topologies have been proposed in the literature.

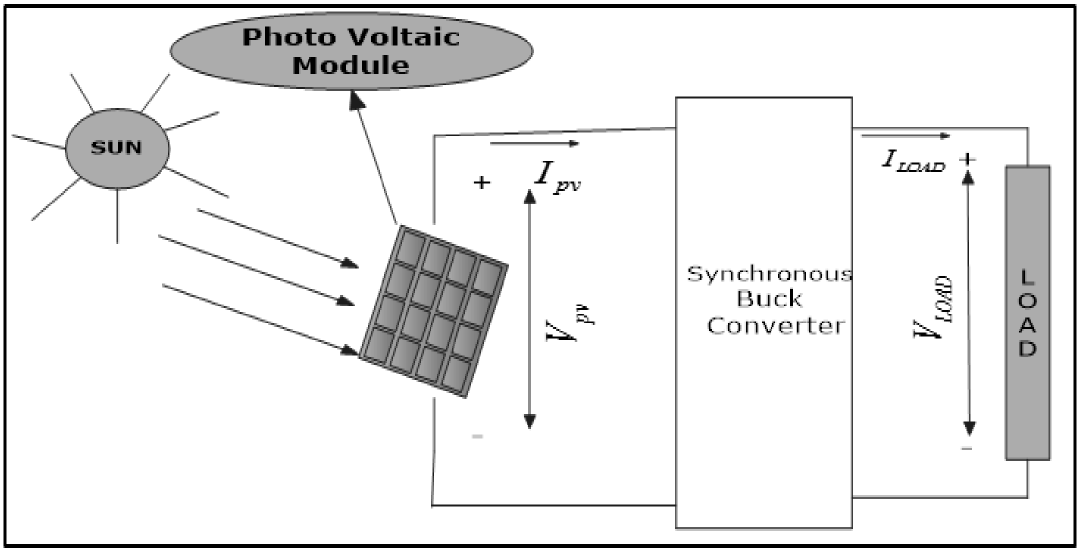

Figure 1: Schematic Diagram of PV Based Converter System.

As shown in the above Figure Fig.1 the dc voltage obtained from the PV array is regulated through dc-dc converter before it is fed to load. As we know the efficiency of solar PV array is very low, so it is of utmost important task of the designer to design dc-dc converter with the appropriate topology to obtain maximum efficiency and also with less cost.

1.3 SYNCHRONOUS BUCK CONVERTER-AN INTRODUCTION:

In the conventional buck converter usually switching losses are high due to high switching frequency operation of MOSFET and losses in freewheeling diode is more due to larger forward voltage drop and consequently the overall efficiency is degraded to a great extent. The Synchronous Buck Converter proposed in [3] has an exquisite design with different modes of operation and with excellent response, but the design is very complex and more elements are involved in the circuit and as a result the solution is not cost effective. In the converter [4], where a keen design of PID Controller is proposed and implemented, it doesn't depict the source dynamics of the converter during source variations. The converter in [5] is real time implemented in FPGA environment, but the overall efficiency of the converter is not discussed. So far many mathematical models for designing the control circuit for converters were presented but nowhere the splendid and simple design and interfacing of practical PV System with Synchronous Buck Converter was discussed.

Synchronous MOSFET is clamped by a Schottky rectifier; it prevents the MOSFET's intrinsic body diode from conducting which prevents the body diode from developing a stored charge. The body diode in a MOSFET is a slow rectifier and would add significant losses if it were allowed to switch. Because the MOSFET rectifier (synchronous rectifier) switches with less than a volt across itself, the switching losses are almost zero compared to conduction losses. And then we conclude that the Synchronous Buck Converter obtained by clamping Schottky rectifier across synchronous switch is far more efficient.

1.4 OVERVIEW OF PROPOSED WORK DONE:

Many literatures are used to carry out the project which includes notes on photovoltaic arrays, PV energy systems, converters topology, variation in the performance of arrays with atmospheric conditions, etc. Reference [1]-[6] gives an overview about the applications of photovoltaic technology. Reference [7] tells about the converter requirement for photovoltaic applications. Various converter topologies have been proposed in the available literature [8]-[9] which describe various such converters available for use. In the conventional buck converter usually switching losses are high due to high switching frequency operation of MOSFET and losses in freewheeling diode is more due to larger forward voltage drop and consequently the overall efficiency is degraded to a great extent. The Synchronous Buck Converter proposed in [3] has an exquisite design with different modes of operation and with excellent response, but the design is very complex and more elements are involved in the circuit and as a result the solution is not cost effective. In the converter [4], where a keen design of PID Controller is proposed and implemented, it doesn't depict the source dynamics of the converter during source variations. The converter in [5] is real time implemented in FPGA environment, but the overall efficiency of the converter is not discussed. So far many mathematical models for designing the control circuit for converters were presented but nowhere the splendid and simple design and interfacing of practical PV System with Synchronous Buck Converter was discussed.

We later extend our converter design to closed loop design using mathematical State Space Modeling. And the study of Maximum Power Point Tracking (MPPT) in PV Energy Systems, and also to be implemented in the proposed converter.

1.5 THESIS OBJECTIVES:

The objectives are hopefully to be achieved at the end of the project:

1. To study the solar cell model and observe its characteristics.
2. To study the proposed synchronous DC-DC buck converter and its operation.
3. To study the design of closed loop with controller with the help of State-Space Modeling.
4. To study the comparison between the conventional DC-DC buck converter and the proposed synchronous DC-DC buck converter in terms of efficiency improvement.
5. To study the Maximum Power Point Tracking (MPPT) algorithms of PV Energy system and to implement in Simulink Environment.
6. To validate the experimental results obtained from the laboratory set-up and to analyze the results with the simulated results in the MATLAB-Simulink Environment.

1.6 ORGANISATION OF THESIS:

The thesis is organized into six chapters including the chapter of introduction. Each chapter is different from the other and is described along with the necessary theory required to comprehend it.

Chapter No.2 deals with PV Array Characteristics and its modelling. First, the equivalent mathematical modelling of the solar cell is made after studying various representations and simplification is made for our purpose. Then PV and IV characteristics curves for both constant temperature and constant irradiation for the equivalent model is studied in MATLAB-Simulink environment using the equation corresponding to that model.

Chapter No.3 deals with the design of various components of Synchronous Buck Converter such as inductor, input capacitor, output capacitor, MOSFET etc., and this section also deals with the comparison between Synchronous Buck Converter and Conventional Buck Converter, especially in the perspective of efficiency.

Chapter No.4 deals with the whole concept of State Space Modeling, and merits of it. And eventually state space equations of the proposed Synchronous Buck Converter is derived in this section, thus obtaining A,B,C and D matrices for the later evaluations during control feedback designing. Which later on used to study the Steady State Response, Response during Step changes in load, Dynamic response while considering the effect of temperature and irradiance changes which effects the input voltage of Synchronous Buck Converter.

Chapter No.5 deals with the study of Maximum Power Point Tracking and its significance in PV Energy systems. And later on we adopt P and O algorithm in MATLAB/Simulink to design the MPPT controller to track and operate at maximum power point for the proposed PV Energy system.

Chapter No.6 is results and discussion section, in which all simulation results such as PV Characteristics, Steady State Simulation of converter, and Simulation during step changes in load of converter, Dynamic operation of converter, efficiency comparison etc., which are obtained in before sections are displayed and explained each result meticulously. Also the experimental results for conventional buck converter and synchronous buck converter are depicted and elucidated.

CHAPTER **2**

PV-Array Characteristics

2.1 INTRODUCTION:

Learning and analyzing PV Array characteristics plays a vital role when it comes to PV energy generation. These characteristics vary from one model to the other. But, however we in this section study the PV array characteristics for ideal PV Cell, which includes P-V and I-V characteristics during constant temperature and also P-V and I-V characteristics during constant Irradiance. Meticulous study of these characteristics helps us to understand the functioning of PV Cell during the variations of temperature and irradiation which are the pioneer parameters for PV energy generation.

These characteristics obtained, not only helps us in understanding PV system, but also helps in the study of concept Maximum Power Point Tracking (MPPT) and also to obtain that point for maximum efficient operation of System. These topics are discussed in later chapters in detail.

2.2 PV ARRAY MODELING:

The solar cell arrays or PV arrays are usually constructed out of small identical building blocks of single solar cell units. They determine the rated output voltage and current that can be drawn for a given set of atmospheric data. The rated current is given by the number of parallel paths of solar cells and the rated voltage of the array depends on the number of solar cells connected in series in each of the parallel paths. A single PV cell is a photodiode. The single cell equivalent circuit model consists of a current source dependent on irradiation and temperature, a diode that conducts reverse saturation current, forward series resistance of the cell.

In the Figure 2, is an approximated version of actual single cell equivalent circuit, the output current (I_{pv}) and the output voltage (V_{pv}) are dependent on the solar irradiation and temperature and also the saturation current of diode. For that single cell, I_{pv} and V_{pv} are calculated by the equations given below:

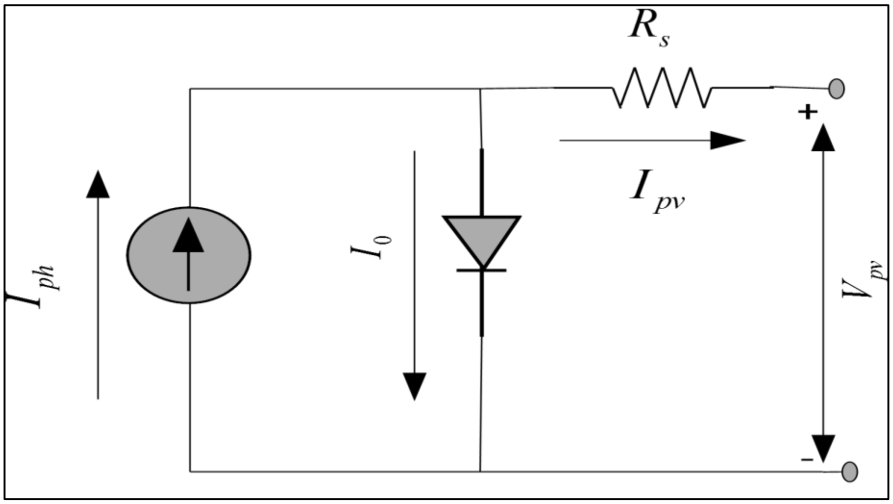

Figure 2: Equivalent Circuit of PV Cell

EQUATIONS:

Module Photo Current:

$$I_{ph} = [I_{SCr} + K_i(T - 298)] * \lambda / 1000 \qquad (1)$$

Module Reverse Saturation Current:

$$I_{rs} = I_{SCr} / [\exp(\frac{qV_{OC}}{N_s kAT}) - 1] \qquad (2)$$

The module saturation Current I_0 varies with the cell temperature as given by:

$$I_0 = I_{rs}[\frac{T}{T_r}]^3 \exp[\frac{q * E_{g0}}{Bk}\{\frac{1}{T_r} - \frac{1}{T}\}] \qquad (3)$$

The Current output of PV Module is:

$$I_{pv} = N_p * I_{ph} - N_p * I_0[\exp\{\frac{q * (V_{pv} + I_{pv}R_s)}{N_s AkT}\} - 1] \qquad (4)$$

With the help of above equations subsystems are created in MATLAB/Simulink environment to obtain PV cell equivalent subsystem and with the help of obtained subsystem PV Characteristics are obtained.

The solar array mainly depends up on three factors: (i) Load current, (ii) Ambient temperature and (iii) Solar irradiation. They are observed as,

(i) When load current increases the voltage drops in the PV array.

(ii) When the temperature increases the output power reduces due to increased internal resistance across the cell.

(iii) When irradiation level increases, the output power increases as more photons knock out electrons and more current flow causing greater recombination.

The variation of output power acts as a function of cell voltage and is affected by different operating conditions. Also output I-V characteristics of the single cell model are observed under various conditions of temperature and solar irradiation. The concerned simulations results are obtained under MATLAB-Simulink environment and are given in results and discussion section.

The obtained results are depicted in the RESULTS AND DISCUSSION Section, under the figure numbers Fig. 8, Fig. 9, Fig. 10 and Fig. 11

CHAPTER **3**

State Space Modelling of Synchronous Buck Converter

3.1 MOTIVATION:

The performance of closed loop converter is highly influenced by PI control parameters. Auto tuning controller improves dynamic response efficiency and reliability. The main idea of auto-tuning is presented as: first system identification is executed and then control parameters are tuned [10].Various methods are introduced to adjust the controller terms. In our project, mathematical modeling of buck converter using State space averaging technique is implemented for this purpose. From the above obtained A, B, C and D matrices, we can obtain the K_P and K_I values of the PI Controller by State space modeling of synchronous buck converter using MATLAB commands ‘sys=ss(A,B,C,D)’ and ’sisotool(sys)’. Then by the result windows obtained by sisotool we select the automated PID tuning option to obtain the K_P and K_I values, and which includes the frequency response of closed loop system. SISO design tool automatically designs interactive compensator design.

The complete closed loop control structure of synchronous buck converter is illustrated in Fig. 3 and the load voltage is compared with reference value, error voltage is generated. The resultant error is fed to PI controller. PI Controller attempts to correct the error between voltage variable measured and a desired voltage (reference) value by calculating and then outputting a corrective action that can adjust the process accordingly. As we know PI controller involves two separate variables: the Proportional and the Integral values. The integral term added to the proportional term accelerates the movement of process towards reference voltage and eliminates the residual steady-state error that occurs with a P controller. The amplified error voltage so obtained is passed through Hysteresis control limiter which limits the value obtained by PID controller to certain value. By using pulse-width modulation (PWM) control regulation of output voltage is achieved by varying the duty cycle of the switches synchronously.

This whole process is possible only after the calculation of state space matrices A, B, C and D, whose derivations are elucidated in the following section.

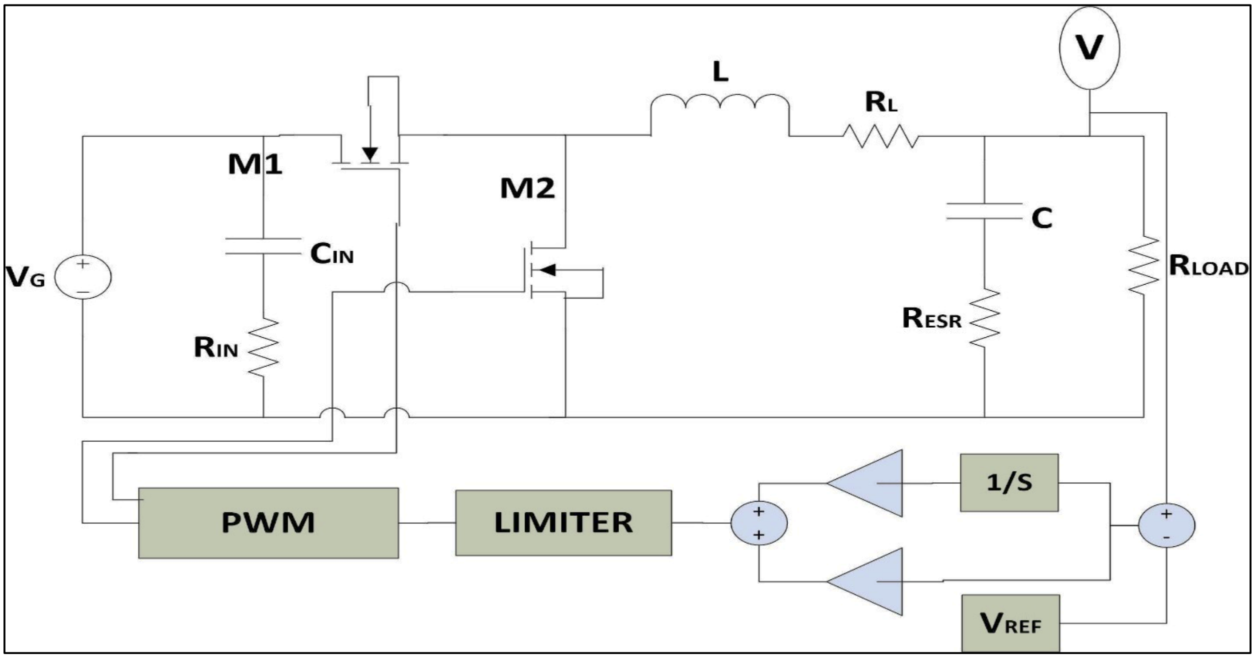

Figure 3: Schematic of closed loop control algorithm of Synchronous Buck Converter.

3.2 STATE SPACE MODELING:

In order to analyze our system, it is essential to reduce the complexity of the mathematical expressions, as well as to resort to computers for most of the tedious computations necessary in the analysis, state-space approach is best suited for this purpose [10]. In literature this state space averaging is the modeling structure given.

Since there is the presentation of accurate mathematical modeling of the system, it helps us obtaining precise K_P and K_I values during PID tuning, which in turn plays a major role in the accurate and exquisite response of closed loop system.

To get proper dynamic equation for synchronous buck converter, we define the two phase of switches (ON and OFF). The network has two energy storage elements: a capacitor C and an inductor L. Assuming voltage across capacitor and current through inductor at t=0 is zero. The only means of selection of state variables is I_L and V_C.

3.2.1 ON STATE EQUATIONS:

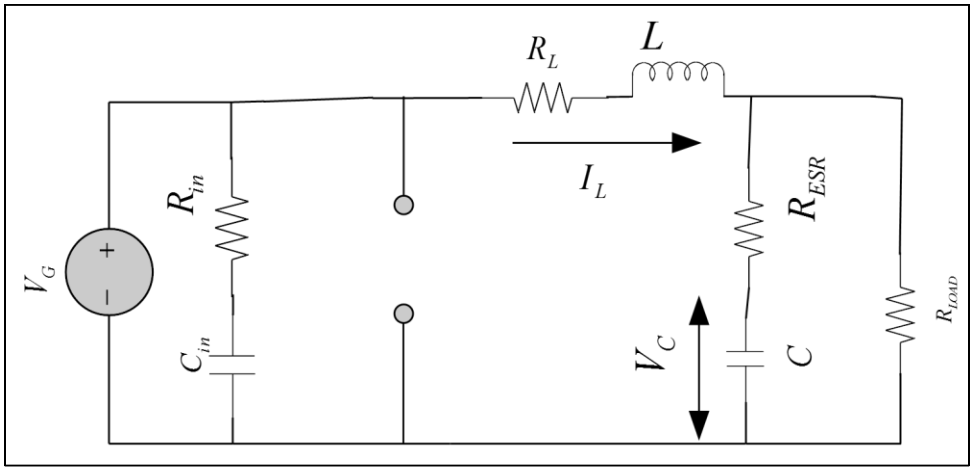

Figure 4: On-State Circuit Diagram of Synchronous Buck Converter

From Fig.4:

V_C and **I_L** state variables,

$$V_G - I_L R_L - L\frac{dI_L}{dt} = V_C + R_{ESR} C\frac{dV_C}{dt} \tag{5}$$

$$I_L = C\frac{dV_C}{dt} + \frac{V_{OUT}}{R_{LOAD}}$$

$$I_L = C\frac{dV_C}{dt} + \frac{V_C + R_{ESR} C\frac{dV_C}{dt}}{R_{LOAD}} \tag{6}$$

$$\frac{dV_C}{dt} = \frac{I_L}{C(1+\frac{R_{ESR}}{R_{LOAD}})} - \frac{V_C}{R_{LOAD} C(1+\frac{R_{ESR}}{R_{LOAD}})} \tag{7}$$

From equations (5) & (6)

$$\frac{dI_L}{dt} = -\frac{I_L}{L}(R_L + \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) + \frac{V_C}{L}(1+\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) + \frac{V_G}{L}$$

From above equation (7)

$$\begin{bmatrix} \dfrac{dI_L}{dt} \\ \\ \dfrac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{L}(R_L + \dfrac{R_{ESR}}{1+\dfrac{R_{ESR}}{R_{LOAD}}}) & \dfrac{1}{L}(-1+\dfrac{R_{ESR}}{R_{LOAD}(1+\dfrac{R_{ESR}}{R_{LOAD}})}) \\ \dfrac{1}{C(1+\dfrac{R_{ESR}}{R_{LOAD}})} & -\dfrac{1}{R_{LOAD}C(1+\dfrac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} I_L \\ \\ V_C \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} \\ \\ 0 \end{bmatrix} V_G$$

$$\Rightarrow \begin{bmatrix} \dot{X}_1 \\ \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{L}(R_L + \dfrac{R_{ESR}}{1+\dfrac{R_{ESR}}{R_{LOAD}}}) & \dfrac{1}{L}(-1+\dfrac{R_{ESR}}{R_{LOAD}(1+\dfrac{R_{ESR}}{R_{LOAD}})}) \\ \dfrac{1}{C(1+\dfrac{R_{ESR}}{R_{LOAD}})} & -\dfrac{1}{R_{LOAD}C(1+\dfrac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ \\ X_2 \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} \\ \\ 0 \end{bmatrix} V_G$$

From Fig.4:

$$V_{OUT} = V_C + R_{ESR} C \frac{dV_C}{dt} \tag{8}$$

From equation (7) & (8)

$$V_{OUT} = V_C (1 - \frac{R_{ESR}}{R_{LOAD}(1+\dfrac{R_{ESR}}{R_{LOAD}})}) + I_L (\frac{R_{ESR}}{1+\dfrac{R_{ESR}}{R_{LOAD}}}) \tag{9}$$

$$V_{OUT} = \begin{bmatrix} \dfrac{R_{ESR}}{1+\dfrac{R_{ESR}}{R_{LOAD}}} & 1-\dfrac{R_{ESR}}{R_{LOAD}(1+\dfrac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} I_L \\ \\ V_C \end{bmatrix}$$

$$\Rightarrow Y = \begin{bmatrix} \dfrac{R_{ESR}}{1+\dfrac{R_{ESR}}{R_{LOAD}}} & 1-\dfrac{R_{ESR}}{R_{LOAD}(1+\dfrac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \\ 0 \end{bmatrix} U$$

3.2.2 OFF STATE EQUATIONS:

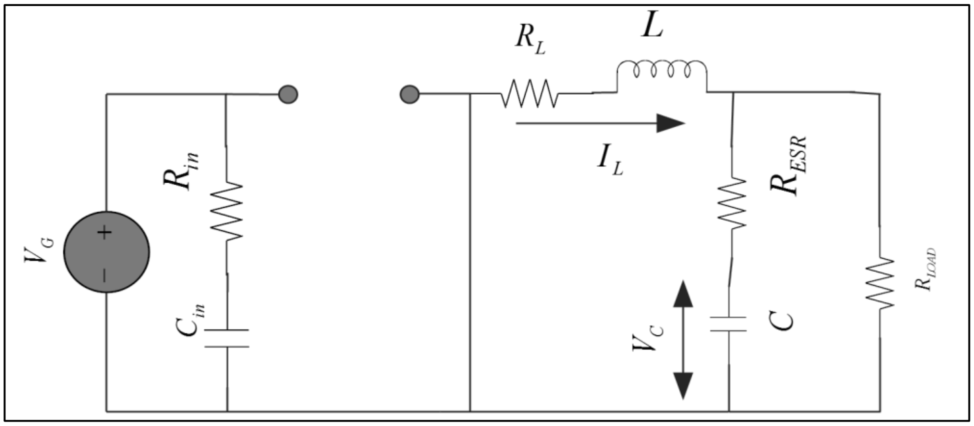

Fig.5: Off-State Circuit Diagram of Synchronous Buck Converter

From Fig. 5:

$$I_L = C\frac{dV_C}{dt} + \frac{V_{OUT}}{R_{LOAD}} \tag{10}$$

$$I_L R_L + L\frac{dI_L}{dt} = V_C + R_{ESR} C\frac{dV_C}{dt} \tag{11}$$

$$V_{OUT} = V_C + R_{ESR} C\frac{dV_C}{dt} \tag{12}$$

From equations (10) & (12)

$$\frac{dV_C}{dt} = \frac{I_L}{C(1+\frac{R_{ESR}}{R_{LOAD}})} - \frac{V_C}{CR_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})} \tag{13}$$

From equations (11) & (13)

$$\frac{dI_L}{dt} = -\frac{I_L}{L}(\frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}} + R_L) + \frac{V_C}{L}(-1+\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) \tag{14}$$

From above equations (13) & (14)

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}(R_L + \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) & \frac{1}{L}(-1+\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) \\ \frac{1}{C(1+\frac{R_{ESR}}{R_{LOAD}})} & -\frac{1}{R_{LOAD}C(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} I_L \\ \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ \\ 0 \end{bmatrix} V_G$$

$$\Rightarrow \begin{bmatrix} \dot{X}_1 \\ \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}(R_L + \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) & \frac{1}{L}(-1+\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) \\ \frac{1}{C(1+\frac{R_{ESR}}{R_{LOAD}})} & -\frac{1}{R_{LOAD}C(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ \\ X_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ \\ 0 \end{bmatrix} V_G$$

From Fig.5:

$$V_{OUT} = V_C + R_{ESR} C \frac{dV_C}{dt}$$

From equations (12) & (13)

$$V_{OUT} = V_C (1 - \frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) + I_L (\frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) \qquad (15)$$

$$\Rightarrow Y = \begin{bmatrix} \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}} & 1-\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \\ 0 \end{bmatrix} U$$

Thus with the help of satate space equations,values of matrice A_1,B_1,C_1, D_1 parameters of ON-State and A_2,B_2,C_2 , D_2 parameters of OFF-State are extracted and A,B,C,D parameters can be obtained as follows:

A=A_1*d+**A_2*(**1-d**);** Where, d is duty ratio

Similarly B, C, and D parameters are also obtained. Thus state space modeling of Synchronous Buck Converter is constructed.

CHAPTER **4**

Synchronous Buck Converter & it's Efficiency

4.1 SYNCHRONOUS BUCK CONVERTER DESIGN:

Converter Design:

The following parameters are considered for design:

- V_{in} = 12 V
- V_{out} = 3 V
- I_{load} = 1 A
- F_{sw} = 200 kHz
- Duty ratio (D) = V_{in}/V_{out} = 0.25
- Assume $I_{ripple} = 0.3*I_{load}$ (typically 30% of load current)
- The switching frequency is selected at 200 kHz.
- The current ripple will be limited to 30% of maximum load.

Parameters Calculations:

a) Inductance Calculation:

Inductor and capacitor plays a major role in dc-dc converters acting like a low pass filter both combined. Inductance helps in limiting the ripple in the output current.

For an inductor,

- $V=L*\delta I/\delta T$

Rearrange and substitute:

$L = (V_{in}-V_{out})*(D/F_{sw})/I_{ripple}$

Calculation:

L=9 V (0.25/200 kHz)/0.3

L=37.5 μH

Assume 37.5 μH, 2 A inductor has a resistance of 0.05Ω The power dissipated due to copper losses is: $(I_{load})^2*ESR = 0.05$ W

b) Output Capacitor Calculation:

The voltage ripple across the output capacitor is the sum of ripple voltages due to the Effective Series resistance (ESR), the voltage sag due to the load current that must be supplied by the capacitor as the inductor is discharged, and the voltage ripple due to the capacitor's Effect Series Inductance. The ESL specification is usually not specified by the capacitor vendor. For this example, we will assume that the ESL value is zero.

As switching frequencies increase, the ESL specification will become more important.

For a capacitor,

- $\delta V=\delta I*(ESR+\delta T/C+ESL/\delta T)$

The equation showed here shows that we are solving an equation with multiple unknowns, ESR, C, and ESL. A reasonable approach is to remove terms that are not significant, and then make a reasonable estimate of the most important parameter that you can control, ESR. The capacitor ESR value was selected from a vendor's catalog of amps rated capacitors. Given the ripple current and the target output voltage ripple, an ESR value of 0.05Ω was selected from a list of capacitors rated for 0.3 amp ripple current.

Assume ripple voltage of 50mV

Given $\delta I=0.3$ A, ESR=0.05Ω

From that, $\delta T=58\mu sec$

Assume ESL=0

Now, we will calculate the required capacitance of the output capacitor given the desired output voltage ripple is defined as 50 mV.

Then, $C_{out}=(\delta I*\delta T)/\ (\delta V-(\delta I*ESR)$

⇨ $C_{out}=500\mu F$

The term in the equation's denominator ($\delta V-(\delta I*ESR)$) shows that the capacitor's ESR rating is more important than the capacitance value. If the selected ESR is too large, the voltage due to the ripple current will equal or exceed the target output voltage ripple. We will have a divide by zero issue, indicating that an infinite output capacitance is required. If a reasonable ESR is selected, then the actual capacitance value is reasonable.

Polymer Electrolytic Capacitor with 500µF and ESR of 0.05Ω is used.

Power loss in the capacitor is $(I_{ripple})^2*ESR=0.0045$ W.

c) Input Capacitor:

The worst case ripple current occurs when the duty cycle is 50% and the worst case ripple current on the input of a buck converter is about one half of the load current. Like the output capacitor, the input capacitor selection is primarily dictated by the ESR requirement needed to meet voltage ripple requirements. Usually, the input voltage ripple requirement is not as stringent as the output voltage ripple requirement. Here, the maximum input voltage ripple was defined as 200 millivolts. The input ripple current rating for the input capacitors may be the most important criteria for selecting the input capacitors. Often the input ripple current will exceed the output ripple current.

Input ripple current is assumed to be $I_{load}/2$

Acceptable input ripple voltage is 200mV

Capacitor ESR value is 0.12Ω

Compute capacitance: $C= \delta T/((V_{ripple}/I_{ripple})-ESR) = 96.6\mu F$

Power loss in the capacitor is $(I_{ripple})^2*ESR= 0.0108$ watts

d) Diode Selection:

The diode's average current is equal to the load current times the portion of time the diode is conducting.

The time the diode is on is: (1 - duty cycle)

$ID = (1-D)* I_{load}= 0.75$ amps

Max diode reverse voltage is 12 volts, for this, select schottky diode 1N5820,

20 V and 3 A rating.

Forward voltage drop assumed at peak current is assumed to be 0.4 volts

Power dissipation in the diode is $V_F*I_d=0.3$ W

e) MOSFET Selection:

To simplify the gate drive circuitry for the MOSFET, a P-channel device was selected. An N-channel device would require a gate drive circuit that incorporates a method to drive the gate voltage about the source. The cost of a level translator and charge pump will outweigh the savings of using an N-channel device versus a P-channel device. A 20 volt MOSFET was not selected because the available devices in the catalog had maximum gate to source voltage ratings of only 12 volts. With a 12 volt input voltage, the applied gate volts might exceed the device specifications. If a 20 volt MOSFET was used, it would be good design practice to incorporate a voltage clamp in the gate driver circuit. A 30 volt device was selected on the basis of the 20 volt gate to source specification. The device current rating is more than necessary, but the low R_{ds}(on) specification minimizes temperature rise. Most small surface mount packages have thermal resistances of about 50 degrees Celsius per watt. With a calculated power dissipation of 0.3 watt, the MOSFET should experience a temperature rise of only 15^0C.

For above design parameters for converter design, select N-channel MOSFET for ease of driving gate. Select 30 V, 9.3 amps with low typically 0.02Ω.

Assume T_{rise}=T_{fall}= 50nsec

Conduction loss= $(I_d)^2$*R_{ds}(on)*D= 0.005watts

Switching loss= ((V_{dif} *I_d/2)*(T_{on} + T_{off})*F_{sw} + C_{oss}*(V_{dif})^2*F_{sw} = 0.0756 watts

(Assume C_{oss}=890pF)

Total loss= 0.005+0.0756= 80mW.

4.2 SYNCHRONOUS BUCK CONVERTER EFFICIENCY AND COMPARISON:

A) Buck Converter Efficiency:

P_{out}= 3 W (3V @ 1a)

Inductor loss= 50mW

Output capacitor loss= 4.5mW

Input capacitor loss= 10.8mW

Diode loss= 300mW

MOSFET loss=80mW

Total losses= 445mW

⇨ Converter efficiency = (*P_{out}/(P_{out}*+Total losses))*100= 87%

Here 60% of total losses are mainly due to diode forward voltage drop (0.4 V). The converter efficiency can be raised if the diode's forward voltage drop will be lowered.

B) Synchronous Buck Converter Efficiency:

This part shows a Synchronous Buck converter. It is similar to the previous asynchronous or conventional buck converter, except the diode is paralleled with another transistor. It is called a synchronous buck converter because MOSFET M2 is switched on and off synchronously with the operation of the primary switch M1. The idea of a synchronous buck converter is to use a MOSFET as a rectifier that has very low forward voltage drop as compared to a standard rectifier. By lowering the diode's voltage drop, the overall efficiency for the buck converter can be improved. The synchronous rectifier (MOSFET M2) requires a second PWM signal that is the complement of the primary PWM signal. M2 is on when M1 is off and vice a versa. This PWM format is called Complementary PWM.

Pout= 3 watts (3 V @ 1 a)

Select N-channel MOSFET with R_{ds}(on) = 0.0044Ω, Use same formula for loss calculation as mentioned above.

Conduction loss= $(I_d)^2 * R_{ds}(on) * (1-D)$ = 15mW

Main MOSFET (M1) loss= 10mW

Resonant capacitor (C_r) loss = 10mW

Resonant Inductor (L_o) loss= 50mW

Output capacitor loss (C_o) =4.5mW

MOSFET (M2) loss= 75mW

Diode (D) loss= 5mW

Inductor (L_r) loss= 20mW

Total Loss = 190mW

⇨ Converter efficiency= (3/3+0.190)*100= 94%

NOTE: The comparative graph of efficiency between Buck Converter and Synchronous Buck Converter is shown in RESULTS AND DISCUSSION section in the Figure 16.

CHAPTER 5

Maximum Power Point Tracking (MPPT)

5.1 INTRODUCTION:

Maximum power point tracking (MPPT) is a technique that grid-tie inverters, solar battery chargers and similar devices use to get the maximum possible power from one or more photovoltaic devices, typically solar panels, though optical power transmission systems can benefit from similar technology. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions. MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads, including power grids, batteries, or motors.

Solar cells are devices that absorb sunlight and convert that solar energy into electrical energy. By wiring solar cells in series, the voltage can be increased; or in parallel, the current. Solar cells are wired together to form a solar panel. Solar panels can be joined to create a solar array.

The Maximum Power Point Tracker (MPPT) is needed to optimize the amount of power obtained from the solar array to the power supply. The output of a solar array is characterized by a performance curve of voltage versus current, called the I-V curve. See Figures Fig. 8 and Fig. 10. The maximum power point of a solar array is the point along the I-V curve that corresponds to the maximum output power possible for the array. This value can be determined by finding the maximum area under the I-V curve. MPPT's are used to correct for the variations in the I-V characteristics of the solar cells. The I-V curve will move and deform depending upon such things as temperature and illumination. For the array to be able to put out the maximum possible amount of power, either the operating voltage or current needs to be controlled.

Since the maximum power point quickly moves as lighting conditions and temperature change, a device is needed that finds the maximum power point and converts that voltage to a voltage equal to the system voltage. Cost is a major factor when deciding to utilize solar energy as a source. As one might expect, a purchaser would want to extract the maximum power per rupee spent on an array. Solar arrays do present an interesting problem in the transfer of energy to a load, however. Since the solar array has a unique I-V relationship similar to a silicon diode, the maximum power point must be tracked to extract the most energy possible.

For more explicit explanation, we can say that solar panels have a nonlinear voltage-current characteristic, with a distinct maximum power point (MPP), which depends on the environmental factors, such as temperature and irradiation. In order to continuously harvest maximum power from the solar panels, they have to operate at their MPP despite the inevitable changes in the environment. This is why the controllers of all solar power electronic converters employ some method for maximum power point tracking (MPPT). Over the past decades many MPPT techniques have been published. The three algorithms that where found most suitable for large and medium size photovoltaic (PV) applications are perturb and observe (P and O), incremental conductance (InCond) and fuzzy logic control (FLC). Here in this project we propose P and O method, which overcome the poor performance when the irradiation changes continuously. This model was validated with simulation.

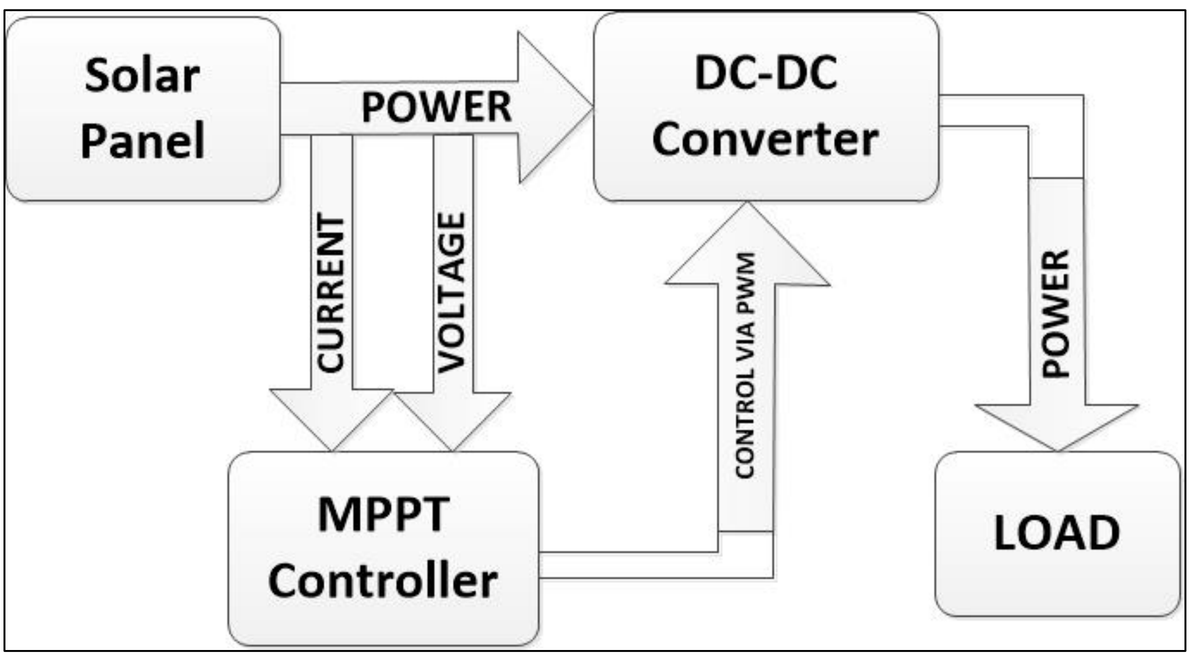

Figure 6: Block diagram of DC-DC converter incorporating MPPT

Above figure Fig. 6 shows a typical feed-forward configuration of DC-DC Converter through MPPT controller which in total aids in tracking Maximum Power Point and makes it evitable for PV Array to operate at Maximum Power Point.

5.2 PERTURB & OBSERVE METHOD:

5.2.1 Motivation:

As was previously explained, MPPT algorithms are necessary in PV applications because the MPP of a solar panel varies with the irradiation and temperature, so the use of MPPT algorithms is required in order to obtain the maximum power from a solar array.

Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity, among others.

Among these techniques, the P&O and the InCond algorithms are the most common. These techniques have the advantage of an easy implementation but they also have drawbacks, as will be shown later. Other techniques based on different principles are fuzzy logic control, neural network, fractional open circuit voltage or short circuit current, current sweep, etc. Most of these methods yield a local maximum and some, like the fractional open circuit voltage or short circuit current, give an approximated MPP, not the exact one. In normal conditions the V-P curve has only one maximum, so it is not a problem. However, if the PV array is partially shaded, there are multiple maxima in these curves. In order to relieve this problem, some algorithms have been implemented as in. In the next section the most popular MPPT techniques are discussed.

5.2.2 Hill Climbing Techniques:

Both P&O and InCond algorithms are based on the “hill-climbing” principle, which consists of moving the operation point of the PV array in the direction in which power increases. Hill-climbing techniques are the most popular MPPT methods due to their ease of implementation and good performance when the irradiation is constant.

The advantages of both methods are the simplicity and low computational. The shortcomings are also well-known: oscillations around the MPP and they can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions. These drawbacks will be explained later.

5.2.3 P&O Algorithm Implementation:

The P&O algorithm is also called “hill-climbing”, but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and PandO a perturbation in the operating voltage of the DC link between the PV array and the power converter. In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique.

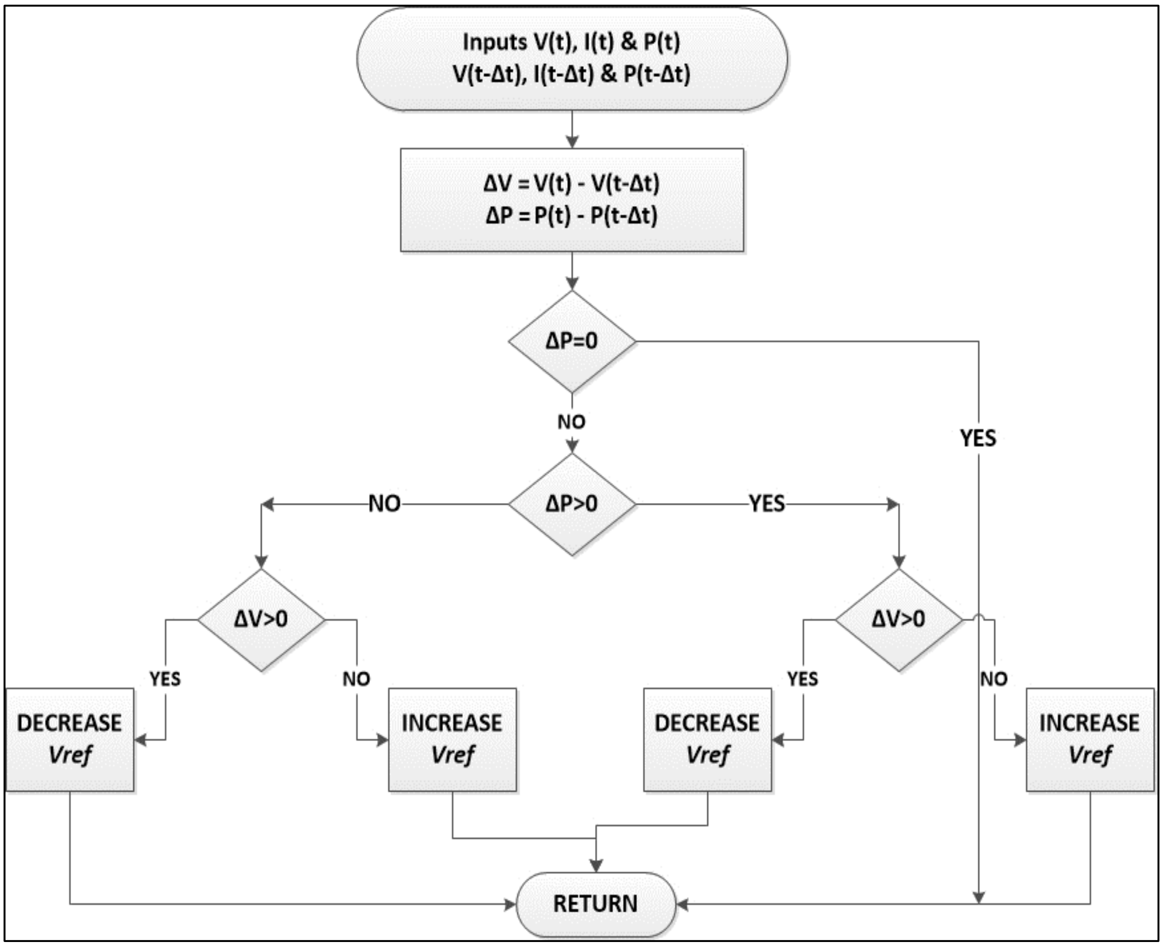

Figure 7: Flow Chart of P&O Algorithm.

In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. As shown in the flow chart above in figure Fig. 7, on the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power.

If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction. Based on these facts, the algorithm is implemented. The process is repeated until the MPP is reached. Then the operating point oscillates around the MPP. This problem is common also to the InCond method, as was mention earlier. A scheme of the algorithm is shown in Figure Fig. 7. In both P and O and InCond schemes, how fast the MPP is reached depends on the size of the increment of the reference voltage. The drawbacks of these techniques are mainly two. The first and main one is that they can easily lose track of the MPP if the irradiation changes rapidly. In case of step changes they track the MPP very well, because the change is instantaneous and the curve does not keep on changing. However, when the irradiation changes following a slope, the curve in which the algorithms are based changes continuously with the irradiation, so the changes in the voltage and current are not only due to the perturbation of the voltage. As a consequence it is not possible for the algorithms to determine whether the change in the power is due to its own voltage increment or due to the change in the irradiation.

When a solar array is used at a source of power, it is necessary to use a maximum power point tracker in ensure minimal energy loss. The maximum power point tracker is implemented to track the maximum power point. This needs to be tracked since due to temperature and illumination the maximum power point will be continuously moving on the I-V curve. In our design, we will implement a Synchronous Buck-Converter and we incorporate MPPT Controller to it and study is carried out in MATLAB-Simulink environment.

Studying the algorithm presented in figure Fig. 7 meticulously, a program is designed in MATLAB-Simulink for the design of MPPT Controller and thus the Maximum Power Point is achieved in the system. This system also includes the PV Array which is designed in Chapter No.2. The obtained results are depicted in RESULTS AND DISCUSSION section.

CHAPTER **6**

Results & Discussions

6.1 PV System:

In order to verify the proposed study of small scale PV system of 19.8 W is considered. This section reveals the simulation results of PV array using the equations depicted in last section in MATLAB/Simulink environment. In this section we will explore the characteristics of PV array with the change in irradiance and temperature and we will observe the changes in output power and current.

Fig.8 depicts the variation of Module current with Module Voltage with the variation of irradiance on the module at the constant temperature i.e. of 30^{o}C.

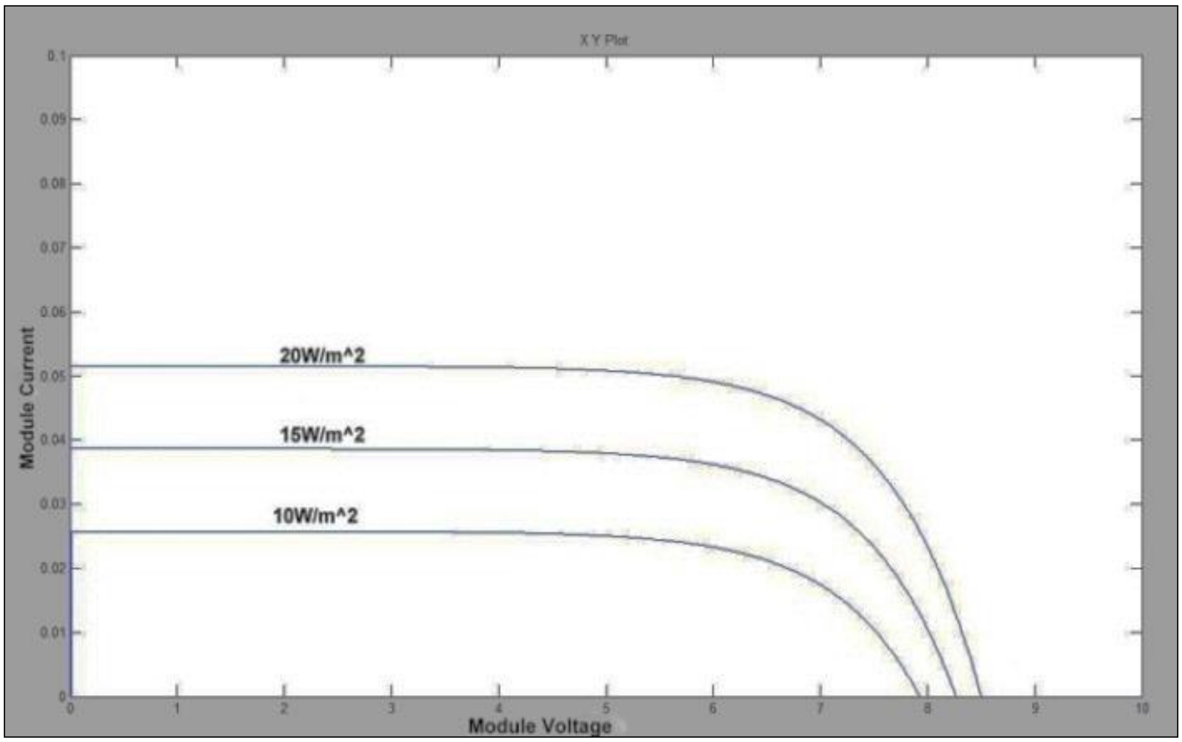

Fig.8 I-V Characteristics at constant temperature.

Fig.9 depicts the variation of Module power with Module Voltage with the variation of irradiance on the module at the constant temperature i.e. of 30^{o}C.

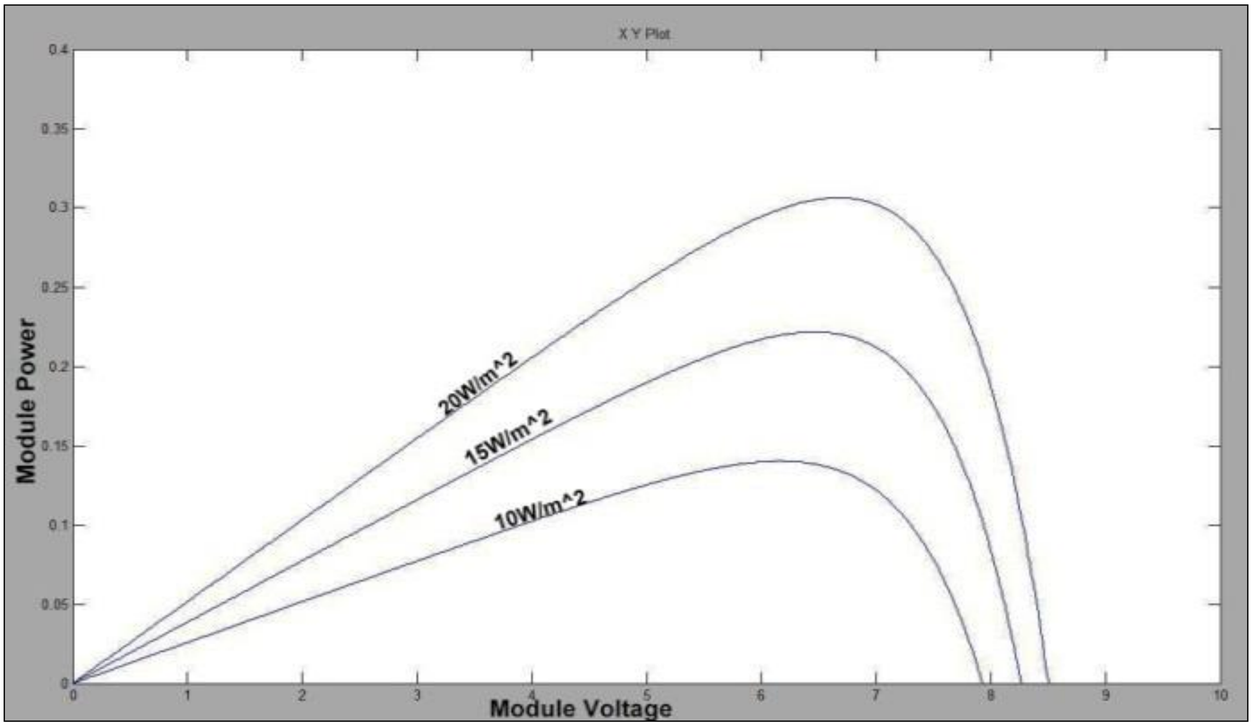

Fig .9: P-V Characteristics at constant temperature

Fig.10 depicts the variation of Module current with Module Voltage with the variation of temperature on the module at the constant irradiance i.e. of $18W/m^2$.

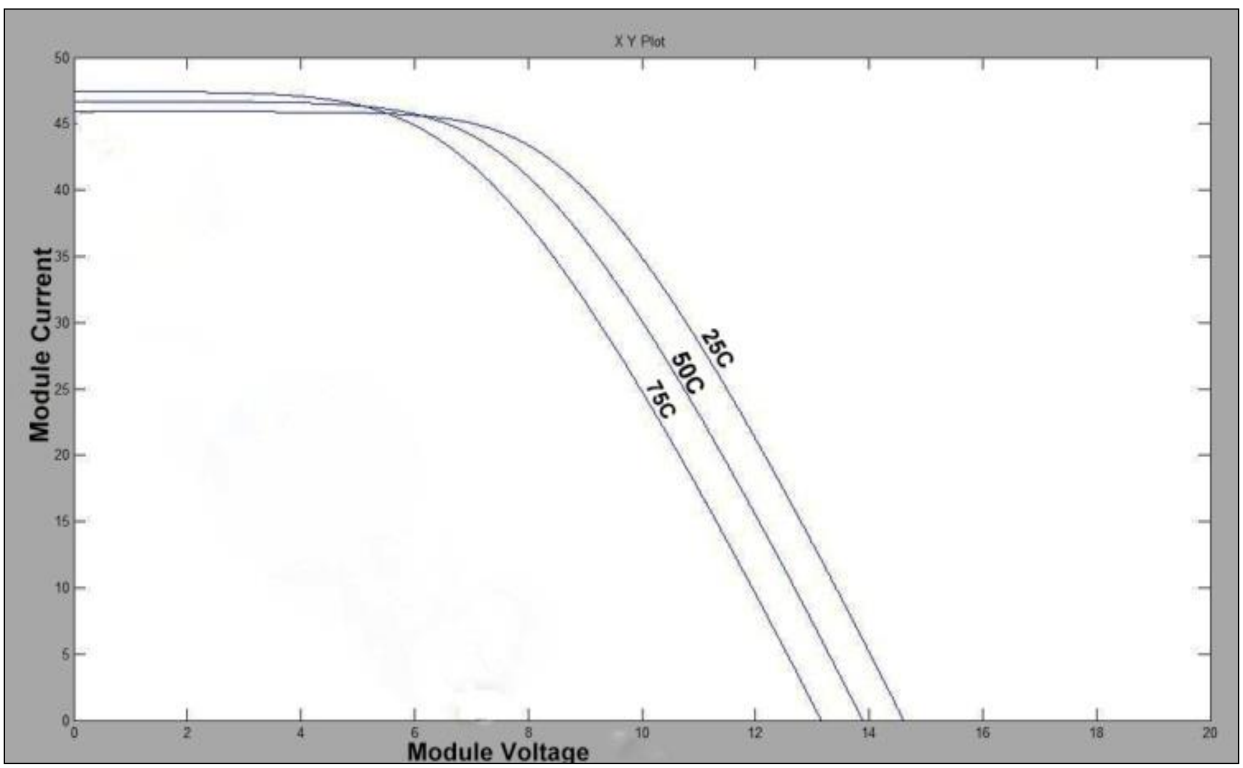

Fig 10. I-V Characteristics at constant irradiance

Fig.11 depicts the variation of Module Power with Module Voltage with the variation of temperature on the module at the constant irradiance i.e. of $18W/m^2$.

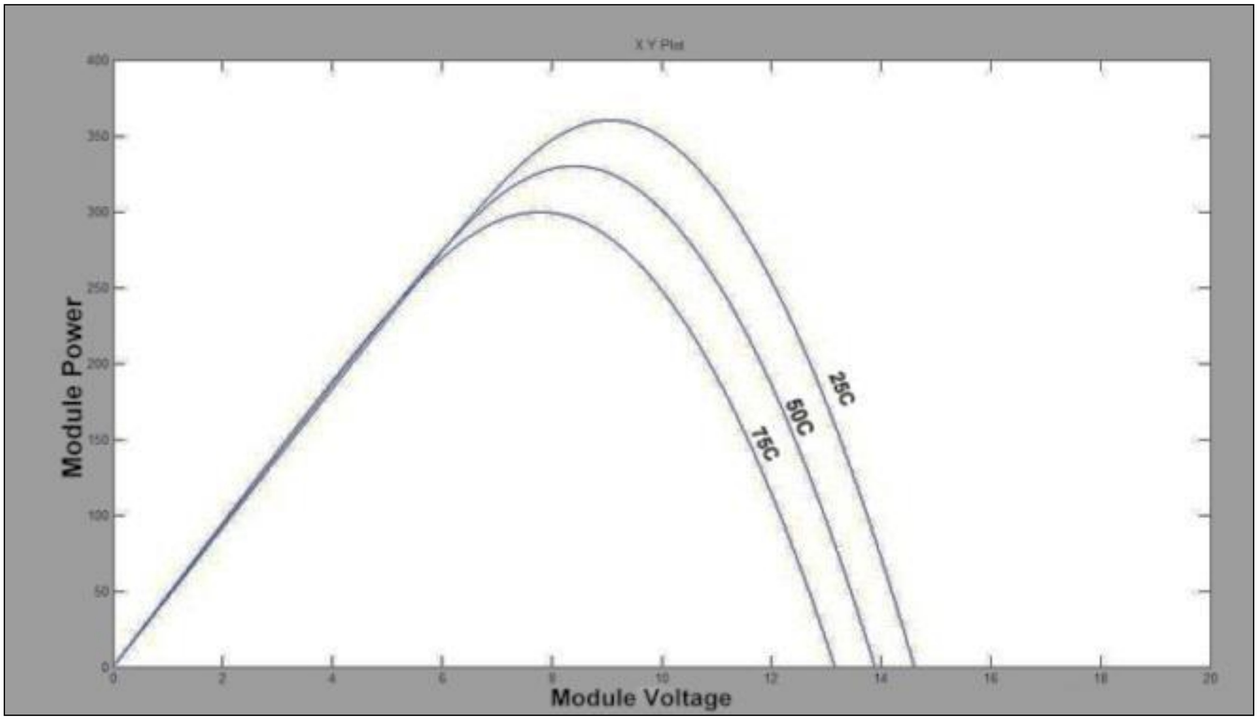

Fig.11. P-V Characteristics at constant irradiance

6.2 Closed Loop Bode Plot of Synchronous Buck Converter:

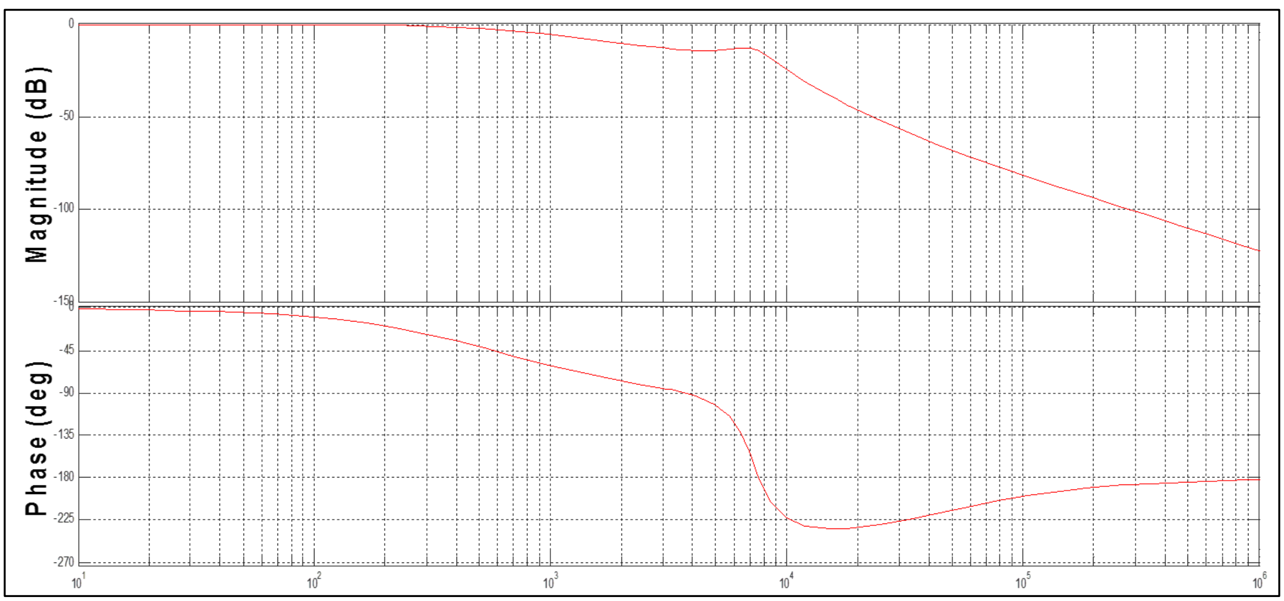

Fig.12.Bode plot of PI controller for Frequency Response

The frequency response of PI controller is plotted using Bode plot which is given in Fig.12. From Fig.12 we could observe that, the Gain Margin=15.9 db. With gain crossover frequency=7.62x103 rad.sec-1, and Phase Margin =88.8deg. With phase crossover frequency=582 rad.sec-1. Since phase crossover frequency is very less than gain crossover frequency, the controller reveals that, the system is highly stable.

6.3 Synchronous Buck Converter:

In order to verify the proposed study of small scale PV system of 19.8 W with dc-dc synchronous buck converter module of is modeled and tested in MATLAB/Simulink environment. The parameters taken for simulation study are given in the appendix. The performance of synchronous buck converter is analyzed under different operating conditions and the corresponding results are presented here.

6.3.1 During Steady State Conditions:

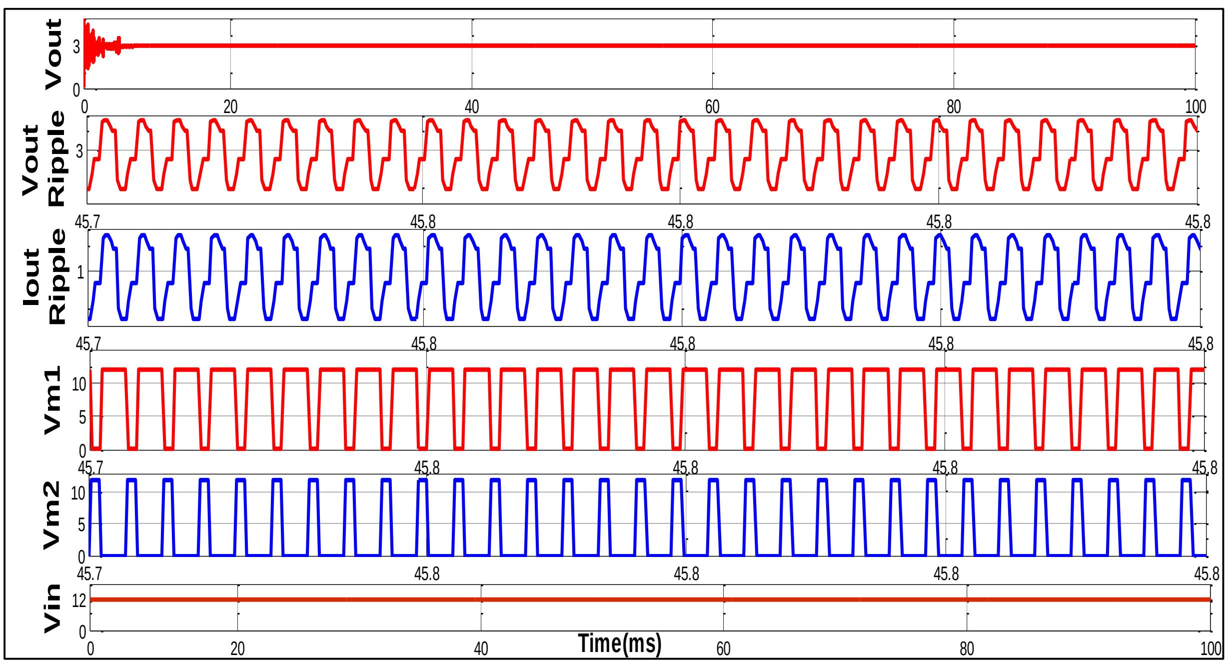

Fig.13. Steady state response of synchronous buck converter (a) Output voltage (b) Output voltage ripple (c) Output current ripple (d) voltage stress across MOSFET "M1" (e) voltage stress across MOSFET "M2" (f) input voltage.

Fig.13 depicts the steady state response of Synchronous Buck Converter for constant load. From Fig.13 (a), one can be see that, the output voltage of the converter settles in less than 6ms with the aid of above designed PI controller. The corresponding output voltage and current ripple are shown in Fig.13 (b) and Fig.13(c) respectively and the voltage and current ripple of output voltage which is maintained very low with the help of the designed output capacitor which limits the output voltage and current ripple. Voltage stress across MOSFET ‘M1’ & MOSFET ‘M2’are illustrated Fig.13(d) and Fig.13(e) with limited values according to desired value. Fig.13(f) shows the response of input voltage from PV system which maintains constant at 12V.

6.3.2 During Step Changes in Load:

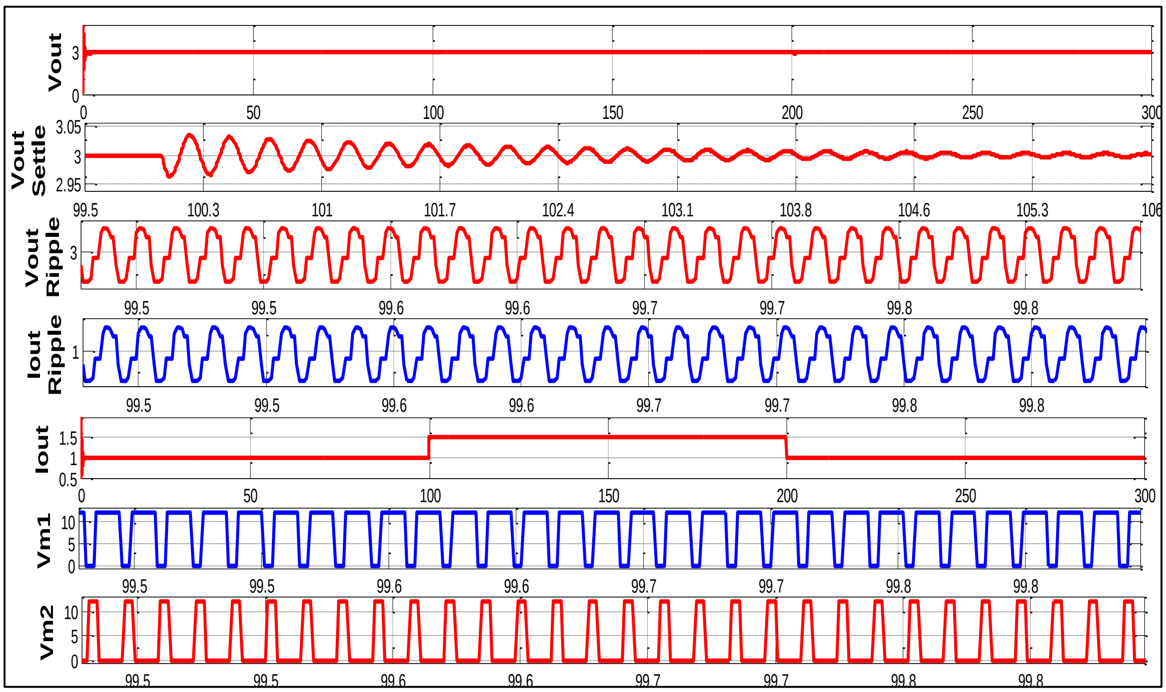

Fig. 14. Response of synchronous buck converter during step changes in the load. (a) Response of Output voltage (b) Settling of output voltage after change in load current. (c) Output voltage ripple (d) Output current ripple (e) Load Current (f) voltage stress across MOSFET “M1” (g) voltage stress across MOSFET “M2”.

Fig.14 depicts the dynamic response of Synchronous Buck Converter during step changes in the load. From Fig.14 (a), we could observe that, the output voltage settles less than 6ms and maintained constant irrespective of the load variation from 1A to 1.5A as illustrated in Fig.14 (d) During load variations, the transients in output voltage persist and it settles within 5ms from the evidence of Fig.14 (b). Voltage stress across MOSFET ‘M1’ & MOSFET ‘M2’are illustrated Fig.14 (d) and Fig.14 (e) with limited values according to desired value. Fig.14 (f) shows the response of input voltage from PV system which maintains constant at 12V.

6.3.3 During Variation of Solar irradiation and Temperature (Source Variation):

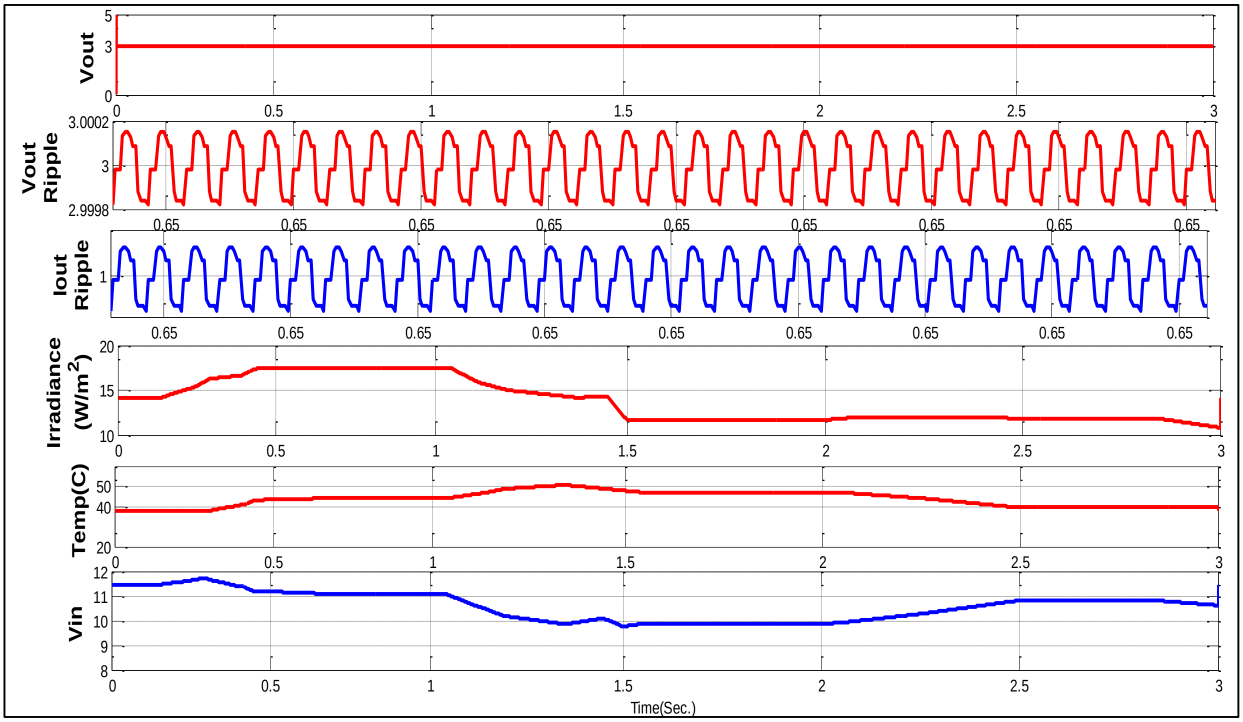

Fig. 15.Dynamics of Synchronous Buck Converter (a) Output voltage (b) Output voltage ripple (c) Output current ripple (d) Solar Irradiation (f) Temperature (g) Output voltage of PV-Array i.e. input to Synchronous Buck Converter.

As illustrated in Fig.15, the source variation is considered as PV is cell possessing highly non-linear characteristics between I_{pv} and V_{pv} due to variation of insolation and temperature. For more realistic study, solar irradiation and temperature is measured at NIT, Rourkela campus from 12 P.M to 3 P.M and are shown in Fig.15 (d) and Fig.15 (e) respectively. Due to variation on these parameters, V_{pv} is also getting varied and is depicted in Fig.15 (e). During this source variation, the controller can able to improve the dynamic response and it maintains the output voltage constant at 3 V and is shown in Fig.15 (a) Fig.15(b) & Fig.15(c) depicts that the output voltage ripple and output current ripple are limited to very less values by the help of high output capacitance.

6.4 Efficiency Comparison:

Fig.16 represents the efficiency comparison between two basic buck converter topologies. Since, voltage drop against MOSFET M2 is lower than the voltage drop across diode in buck converter topology. So, synchronous buck converter has low or less power dissipations and higher efficiency is obtained. From the figure it's evident that, Synchronous Buck Converter has better efficiency than Conventional Buck Converter. The efficiency of synchronous buck converter at light load is higher than non-synchronous buck converter. However, under higher load level, the efficiency also depends on duty cycle. However the tradeoff for better efficiency in Synchronous Buck Converter is the price of additional MOSFET used. And also MOSFET saves space but complexity of control is increased because both switches should not conduct simultaneously. (Any simultaneous conduction could cause to overload and damage the system called as "shoot through". To get rid of this a suitable delay called "dead-time" must be incorporated.)

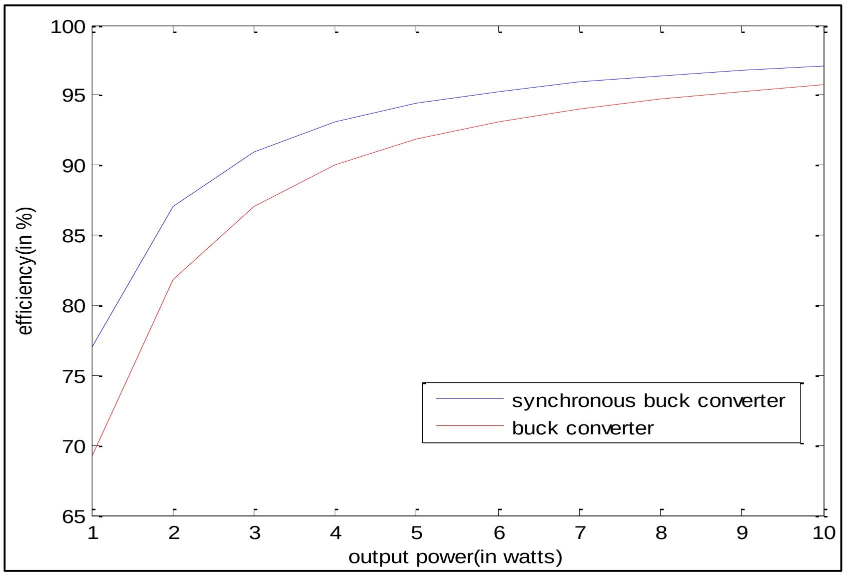

Fig. 16. Efficiency Comparison between Synchronous Buck Converter & Conventional Buck Converter.

6.5 Maximum PowerPoint Tracking:

MPPT technique (P&O Algorithm) is implemented i.e perturbation on the duty cycle of the power converter and a perturbation in the operating voltage of the DC link between the PV array and the power converter is done so that maximum power is extracted from PV panel. As illustrated in Fig.17, PV is cell possessing highly non-linear characteristics between I_{pv} and V_{pv} due to variation of insolation and temperature. Fig.17 (d) and Fig.17 (e) indicates variation of solar irradiation and temperature respectively. Due to variation on these parameters, V_{pv} is also getting varied and is depicted in Fig.17 (c). Converter dynamic response is observed and it is seen that output voltage is maintained constant at 3 V and is shown in Fig.17 (b) and Fig.17 (a) indicates load current.

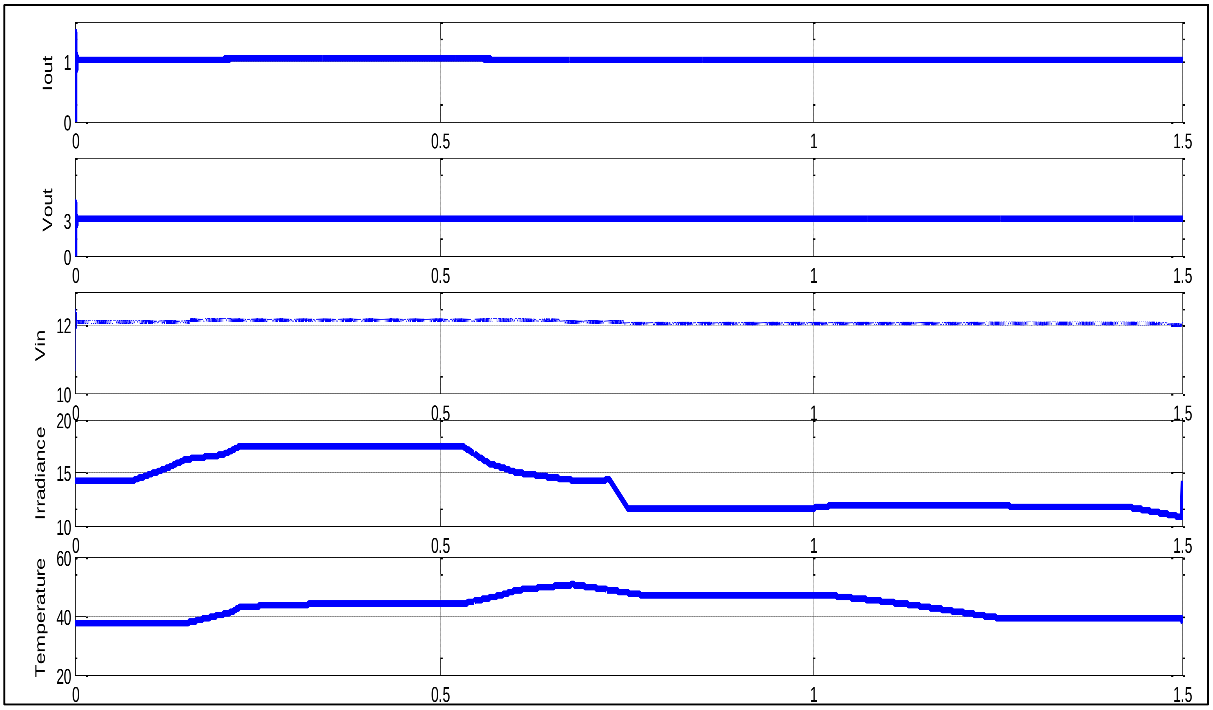

Fig.17 Response of Synchronous Buck Converter using MPPT technique (a) Output current (b) Output voltage (c) output voltage of PV-Array i.e. input to Synchronous Buck Converter. (d)Solar Irradiation (e) Temperature

6.6 EXPERIMENTAL RESULTS:

As discussed in Chapter No.3, various components of Synchronous Buck Converter are designed and bought through stores. The catalogue of items are given below:

- Ready-made Inductor of value around 40µH.
- Input Capacitor of value 100µF
- Output Capacitor of value 500µ
- Two N-Channel MOSFETS i.e. SiHG20N50C
- Two resistors of 1.5Ω each.
- High Voltage and High Speed power MOSFET or IGBT driver IR2213

As shown in the figure Fig. 18, experimental set up in laboratory is going to require Voltage Source, CRO, Bread Boards, Connecting probes, Function generator etc., to carry out the experimental work intended.

We operate at 170 kHz and we use a duty cycle of 50% for flexible operation of the MOSFETs

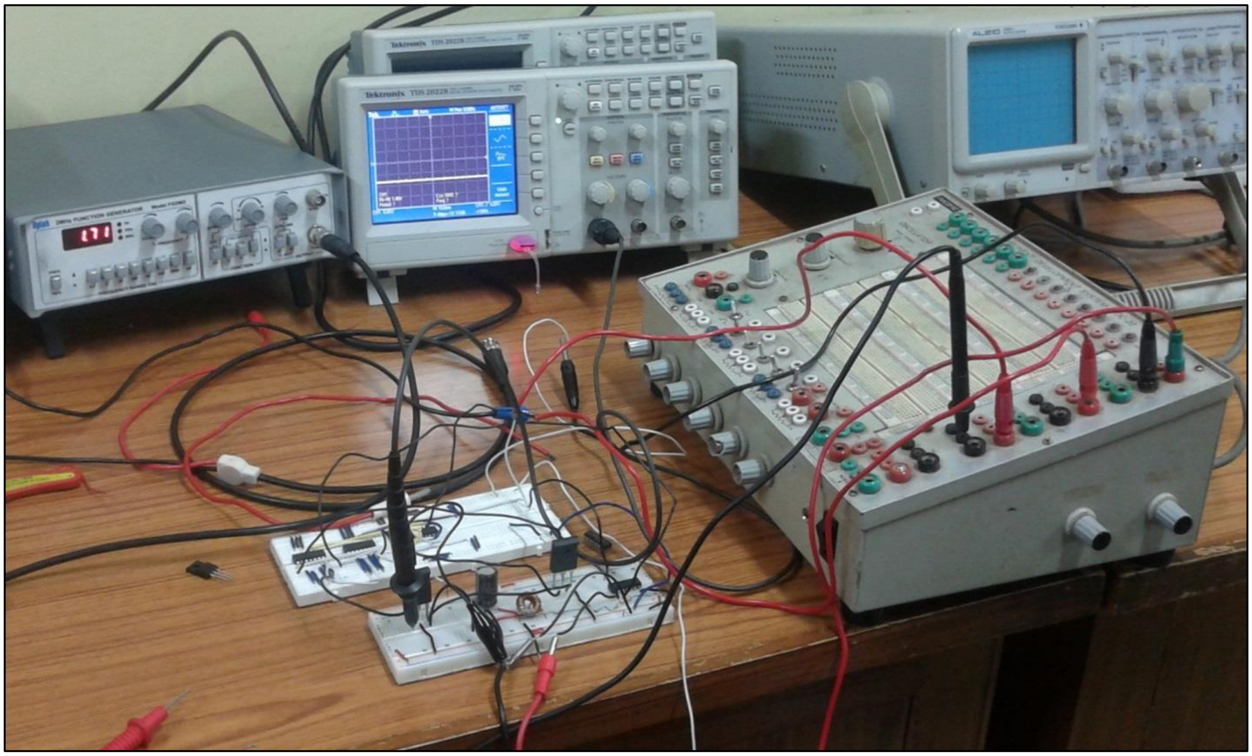

Figure 18: Experimental Set-up in Laboratory

6.6.1 Conventional Buck converter:

Converter Input voltage shown in figure Fig. 19 is given through voltage source for conventional buck converter set-up. With the help of CRO we can observe the obtained output voltage which is shown in the figure Fig. 20, which concurs with the theoretical calculations of Buck Converter.

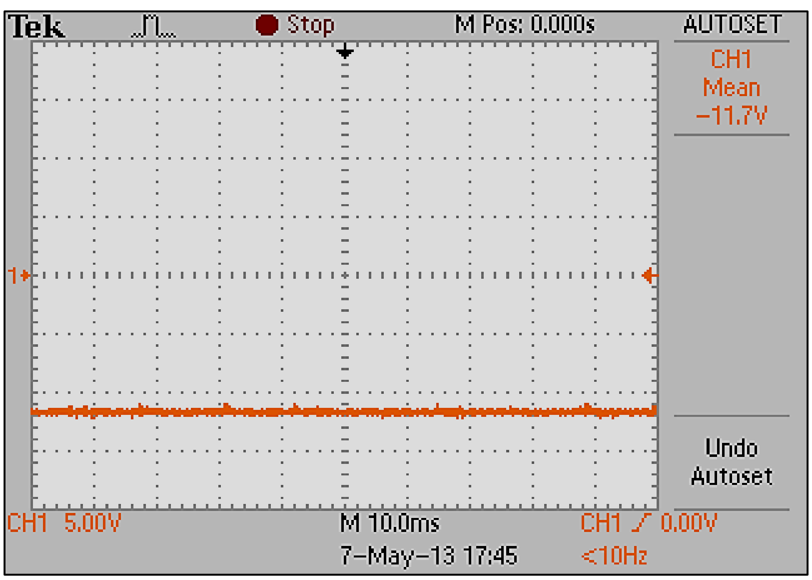

Figure 19: Input Voltage to Buck Converter

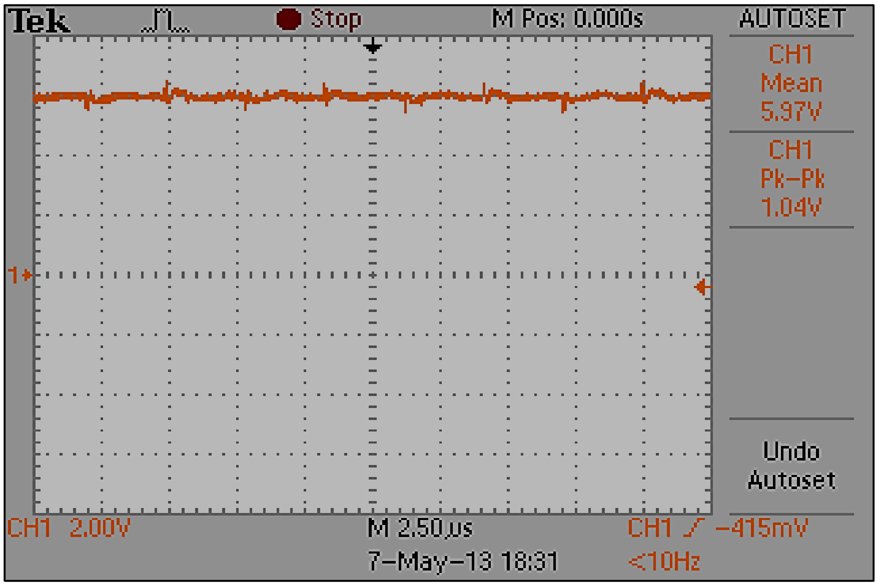

Figure 20: Output Voltage of Buck Converter

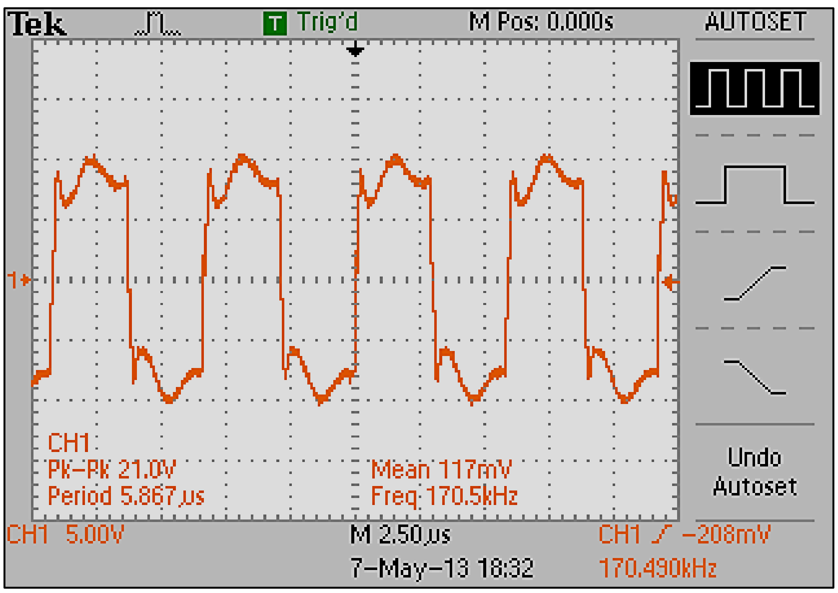

Figure 21: Voltage Across MOSFET

In the above figure Fig. 21 we can observe the voltage stress across the power MOSFET.

6.6.2 Synchronous Buck Converter:

Input voltage same as given to Buck Converter as shown in figure Fig. 19 is given through voltage source for Synchronous buck converter set-up. With the help of CRO we can observe the obtained output voltage which is shown in the figure Fig. 22, which concurs with the theoretical calculations of Buck Converter. In figures Fig. 23 and Fig. 24 we can observe the voltage stress across the main MOSFET and Synchronous MOSFET respectively.

From the figures, Fig. 22 and Fig. 20 it is evident that the output voltages for both Conventional Buck Converter and Synchronous Buck Converter are identical for a given duty cycle. However, as studied theoretically there will be a great deal of difference in the efficiencies in the comparison of both converters, in which Synchronous Buck Converter have more efficiency than Conventional Buck Converter as shown in the figure

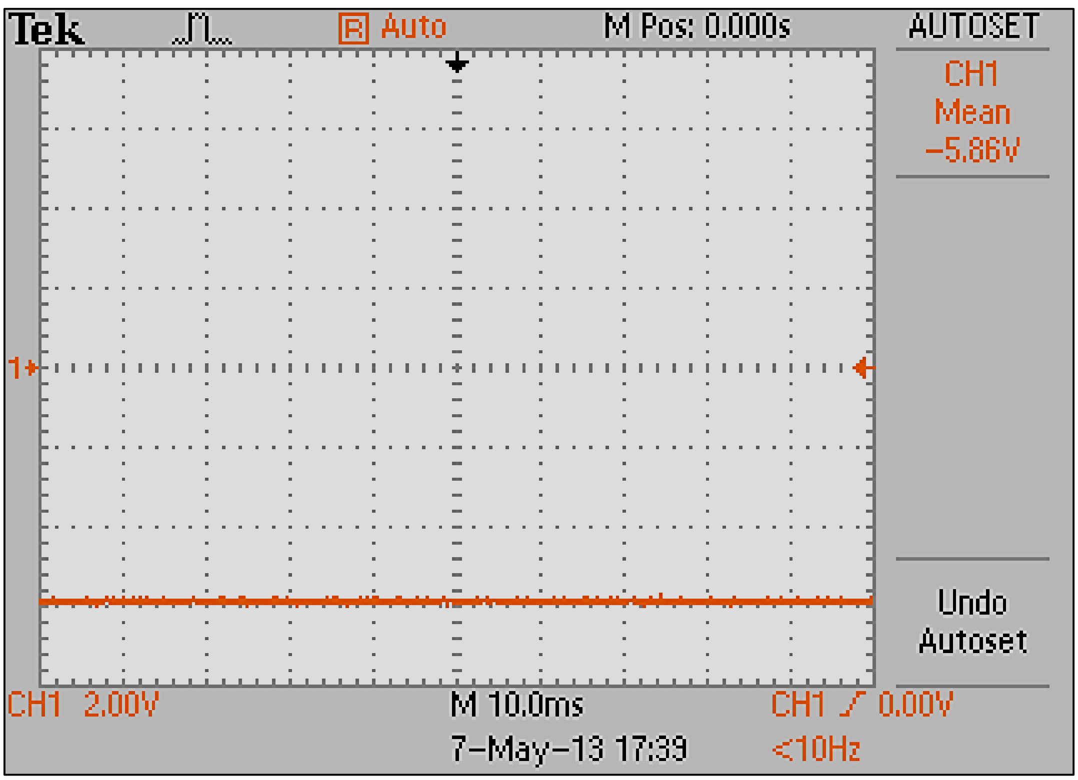

Figure 22: Output Voltage for Synchronous Buck Converter

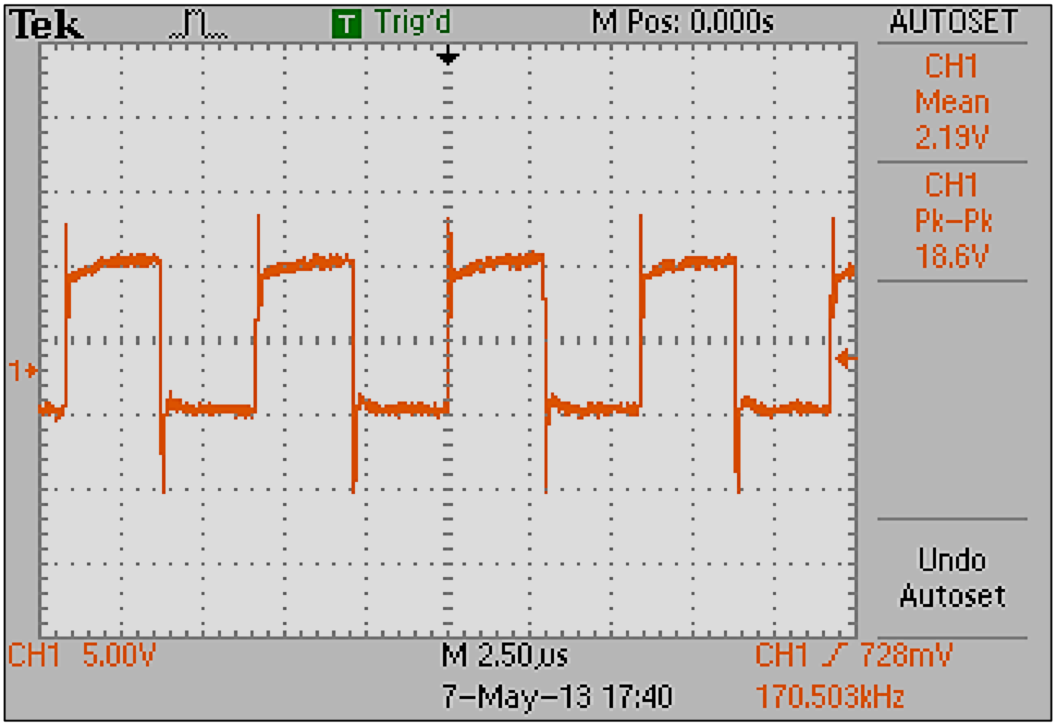

Figure 23: Voltage Across Main MOSFET M1

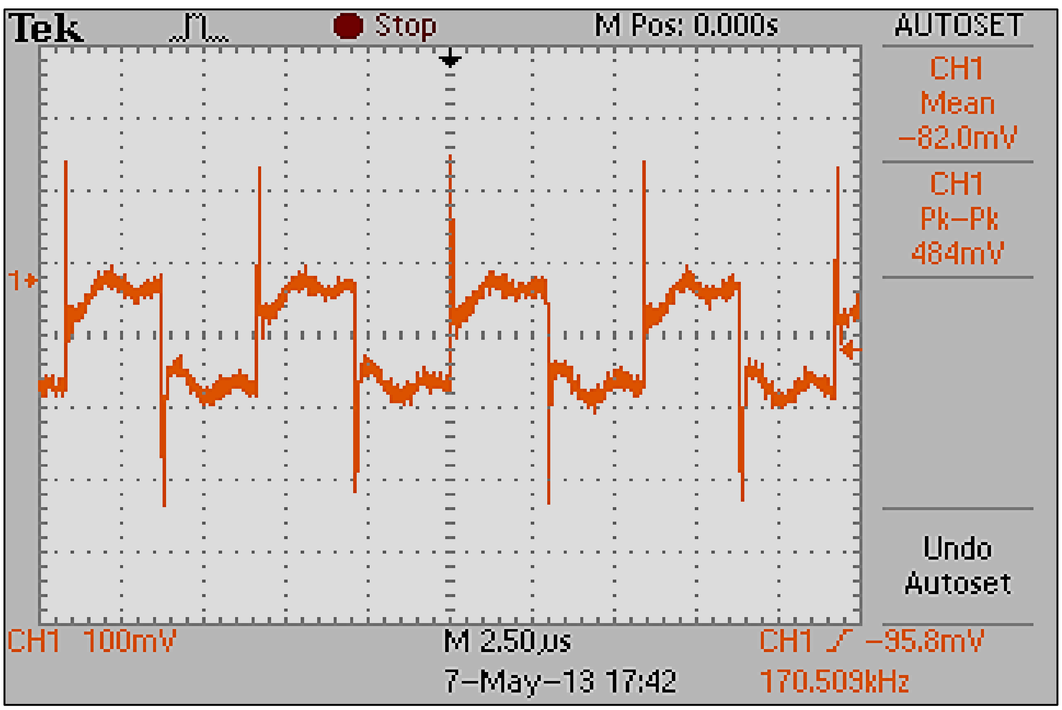

Figure 24: Voltage Across Synchronous MOSFET M2

CONCLUSIONS

In this project, an accurate mathematical modeling and design of synchronous buck converter for low power PV energy system is presented. As solar array is used as a source of power, it is necessary to use a maximum power point tracker to ensure minimal energy loss. The maximum power point tracker is implemented to track the maximum power point in our synchronous buck conveter design. The core idea of paper is to use State Space Averaging technique for modeling of converter which decides precise values for PI controller used in control circuit. Synchronous buck converter with closed loop PI controller precisely improved the dynamic response of the system during load as well as source variation with reduced voltage and current ripple. Moreover, the circuit structure is simpler and much cheaper compared to other control mechanisms where large number of components is needed. Further, the converter design and its efficiency also determined. As results, the efficiency of synchronous buck converter is higher than conventional dc-dc buck converter for same power rating. And the results obtained from the experimental set up, satisfies with the simulation results.

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PAPERS PUBLISHED:

1. Suman Gunda, B.V.S.Pavan Kumar, M.Sagar Kumar, B.Chitti Babu, K.R.Subhashini **"Modeling, Analysis and Design of Synchronous Buck Converter using State Space Averaging Technique for PV Energy System",** *ISED-Conference 2012.*

Modeling, Analysis and Design of Synchronous Buck Converter using State Space Averaging Technique for PV Energy System

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***Abstract*— Abstract-- In this paper, modeling, analysis and design of synchronous buck converter for low power photo-voltaic (PV) energy system is presented. For analyzing the performance such converter, first we studied the characteristics of PV array under different values of irradiance and temperature. Then the exquisite design of Synchronous Buck Converter with the application of State Space Modeling to implement precise control design for the converter is presented. The synchronous Buck Converter thus designed is used for portable appliances such as mobiles, laptops, iPod's laptops, chargers, etc. In addition to that, closed loop control of synchronous buck converter is studied in order to meet the dynamic energy requirement of load especially during variation of source i.e. variation of solar irradiation and temperature. Further, the efficiency of synchronous buck converter is calculated and is compared with conventional buck converter. The studied model of complete system is simulated in the MATLAB/Simulink environment and the results are obtained with closeness to the theoretical study.**

Keywords- PV Array, State Space Averaging, Synchronous Buck Converter, portable applications, PI controller.

INTRODUCTION

At present scenario, the demand of energy is increasing exponentially and on the contrary the fossil fuel used for power generation is depleting. Also fossil fuel based power generation system causes the problem to the environment due to global warming and greenhouse effect. For clean and green energy generation, renewable energy sources such as wind, solar, micro-hydro power generating systems are playing a pivotal role for future energy demand. Hydro Energy generation and Wind Energy generation are of course two of the main sources of renewable energies, but the main disadvantage in Hydro Energy is that, it is seasonal dependent and in Wind energy is that it is geographical location dependent[1]. On the other hand Solar Energy is prevalent all over the globe and all the time. The amount of irradiance and temperature may vary from place to place and from time to time but under given conditions Solar Energy system can be implemented. Solar Energy or PV energy system is the most direct way to convert the solar radiation into electricity based on photovoltaic effect. Despite of high initial costs, they are already have been implemented in many rural areas. In future the cost of the PV panel also may diminish, because of the advancing material technology and also the competition between manufacturers. Thus PV energy system is mainly employed for small scale standalone systems or portable applications. The typical PV system feeds power to the load via power electronics converters is shown in Fig.1.

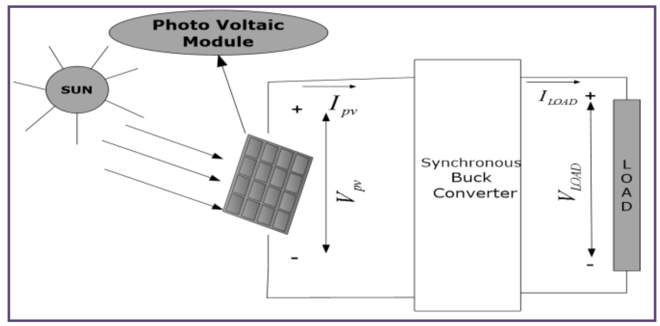

Fig. 1 Schematic Diagram of PV Based Converter System

The output voltage thus obtained from the PV panel is DC. For low power applications, dc-dc converters are employed to step-up or step-down the output DC voltage according to the load requirements. However overall conversion efficiency is very low (typically 6.5%) So accurate modeling and design of dc-dc converter is necessary in order to improve the overall system performance with cost effective solution [2]. Various converter topologies have been proposed in the available literature [3]-[5]. In the conventional buck converter usually switching losses are high due to high switching frequency operation of MOSFET and losses in freewheeling diode is more due to larger forward voltage drop and consequently the overall efficiency is degraded to a great extent. The Synchronous Buck Converter proposed in [4] has an exquisite design with different modes of operation and with excellent response, but the design is very complex and more elements are involved in the circuit and as a result the solution is not cost effective. In the converter [5], where a keen design of PID Controller is proposed and implemented, it doesn't depict the source dynamics of the converter during source variations. The converter in [6] is real time implemented in FPGA environment, but the overall efficiency of the converter is not discussed. So far many mathematical models for designing the control circuit for converters were presented but nowhere the splendid and simple design and interfacing of practical PV System with Synchronous Buck Converter was discussed.

This paper presents modeling and analysis of Synchronous Buck Converter for low power PV energy system application. The converter is modeled using state space averaging technique with simple mathematical equations. For achieving precise dynamic results, PI Controller is designed for which State Space Modeling procedure is presented to compute the Kp and KI values of controller. Further, the efficiency of synchronous buck converter is calculated and is compared with conventional buck converter. Then Schottky rectifier is proposed which is clamped across the Synchronous rectifier, which diminishes the switching losses in Synchronous MOSFET.

The paper is organized as follows: State Space Modeling of synchronous buck converter is analyzed and explained in section II. Further, closed loop control using PI controller is explained in section III and results and discussions are made in Section IV followed by references.

MATHEMATICAL MODELLING FOR CONTROL DESIGN: STATE SPACE ANALYSIS

In order to analyze our system, it is essential to reduce the complexity of the mathematical expressions, as well as to resort to computers for most of the tedious computations necessary in the analysis; *state-space approach* is best suited for this purpose [7]. To get proper dynamic equation for synchronous buck converter, we define the two phase of switches (ON and OFF). The network has two energy storage elements: a capacitor C and an inductor L. Assuming voltage across capacitor and current through inductor at t=0 is zero. The only means of selection of state variables is

- $\mathbf{X_1=I_L}$ & $\mathbf{X_2=V_C}$ (9)

And voltage across $\mathbf{R_{LOAD}}$ as the output variable $(\mathbf{V_{out}}) = \mathbf{y}$, considering input voltage $\mathbf{V_G=U}$.

The state space equations are ,

$$\dot{X} = AX + BU$$

$$\dot{Y} = CX + DU$$

<u>a. During ON State</u> :-

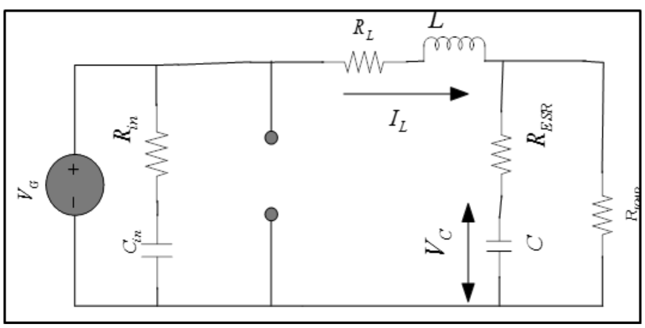

Fig.2 On-State Circuit Diagram of Synchronous Buck Converter

From Fig.3: $\mathbf{V_C}$ and $\mathbf{I_L}$ are state variables,

$$V_G - I_L R_L - L\frac{dI_L}{dt} = V_C + R_{ESR}C\frac{dV_C}{dt} \qquad (5)$$

$$I_L = C\frac{dV_C}{dt} + \frac{V_{OUT}}{R_{LOAD}}$$

$$I_L = C\frac{dV_C}{dt} + \frac{V_C + R_{ESR}C\frac{dV_C}{dt}}{R_{LOAD}} \qquad (6)$$

$$\frac{dV_C}{dt} = \frac{I_L}{C(1+\frac{R_{ESR}}{R_{LOAD}})} - \frac{V_C}{R_{LOAD}C(1+\frac{R_{ESR}}{R_{LOAD}})} \qquad (7)$$

From equations (5) & (6)

$$\frac{dI_L}{dt} = -\frac{I_L}{L}\left(R_L + \frac{R_{ESR}}{(1+\frac{R_{ESR}}{R_{LOAD}})}\right) + \frac{V_C}{L}\left(1+\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}\right) + \frac{V_G}{L}$$

From above equation (7)

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}(R_L + \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) & \frac{1}{L}(-1+\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) \\ \frac{1}{C(1+\frac{R_{ESR}}{R_{LOAD}})} & -\frac{1}{R_{LOAD}C(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_G$$

state equation for this phase is given below:

$$\Rightarrow \begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}(R_L + \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) & \frac{1}{L}(-1+\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) \\ \frac{1}{C(1+\frac{R_{ESR}}{R_{LOAD}})} & -\frac{1}{R_{LOAD}C(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_G$$

From Fig.3:

$$V_{OUT} = V_C + R_{ESR}C\frac{dV_C}{dt} \qquad (8)$$

From equation (7) & (8)

$$V_{OUT} = \begin{bmatrix} \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}} & 1-\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix}$$

$$\Rightarrow Y = \begin{bmatrix} \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}} & 1-\frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} U$$

<u>b. During OFF State</u>:-

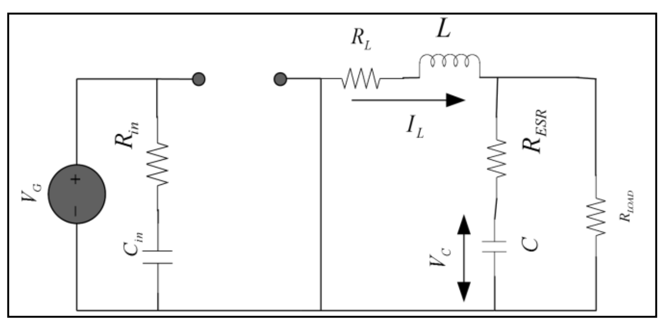

Fig.3 Off-State Circuit Diagram of Synchronous Buck Converter

From Fig. 4:

$$I_L = C\frac{dV_C}{dt} + \frac{V_{OUT}}{R_{LOAD}} \qquad (9)$$

$$I_L R_L + L\frac{dI_L}{dt} = V_C + R_{ESR} C\frac{dV_C}{dt} \qquad (10)$$

$$V_{OUT} = V_C + R_{ESR} C\frac{dV_C}{dt} \qquad (11)$$

From equations (10) & (9)

$$\frac{dV_C}{dt} = \frac{I_L}{C(1+\frac{R_{ESR}}{R_{LOAD}})} - \frac{V_C}{CR_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})} \qquad (12)$$

From equations (10) & (12)

$$\frac{dI_L}{dt} = \frac{I_L}{L}\left(\frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}} - R_L\right) + \frac{V_C}{L}\left(1 - \frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}\right) \qquad (13)$$

From above equations (12) & (13)

$$\begin{bmatrix} \frac{dI_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{L}(-R_L + \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) & \frac{1}{L}(1 - \frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) \\ \frac{1}{C(1+\frac{R_{ESR}}{R_{LOAD}})} & -\frac{1}{R_{LOAD}C(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_G$$

State equation for this phase is given below:

$$\Rightarrow \begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}(R_L + \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}) & \frac{1}{L}(-1 + \frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}) \\ \frac{1}{C(1+\frac{R_{ESR}}{R_{LOAD}})} & -\frac{1}{R_{LOAD}C(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_G$$

Also from equations (12) & (11)

$$V_{OUT} = V_C\left(1 - \frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})}\right) + I_L\left(\frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}}\right) \qquad (14)$$

$$\Rightarrow Y = \begin{bmatrix} \frac{R_{ESR}}{1+\frac{R_{ESR}}{R_{LOAD}}} & 1 - \frac{R_{ESR}}{R_{LOAD}(1+\frac{R_{ESR}}{R_{LOAD}})} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} U$$

Thus with the help of state space equations,values of matrice A_1,B_1,C_1, D_1 parameters of ON-State and A_2,B_2,C_2, D_2 parameters of OFF-State are extracted and A,B,C,D parameters can be obtained as follows:

- **$A=A_1$*d+A_2*(1-d);** where, d is duty ratio.

Similarly B,C and D parameters are also obtained.Thus statespace average model for buckconverter is constructed.

Closed Loop Control Algorithm

The performance of closed loop converter is highly influenced by PI control parameters. Auto tuning controller improves dynamic response efficiency and reliability. The main idea of auto-tuning is presented as: first system identification is executed and then control parameters are tuned [7].Various methods are introduced to adjust the controller terms. In this paper, mathematical modeling of buck converter using State space averaging technique is implemented for this purpose. From the above obtained A, B, C and D matrices, we can obtain the KP and KI values of the PI Controller by State space modeling of synchronous buck converter using MATLAB commands 'sys=ss(A,B,C,D)' and 'sisotool (sys)'. Then by the result windows obtained by sisotool we select the automated PID tuning option to obtain the KP and KI values, and which includes the frequency response of closed loop system. SISO design tool automatically designs interactive compensator design.

The complete closed loop control structure of synchronous buck converter is illustrated in Fig.5 and the load voltage is compared with reference value, error voltage is generated. The resultant error is fed to PI controller. PI Controller attempts to correct the error between voltage variable measured and a desired voltage (reference) value by calculating and then outputting a corrective action that can adjust the process accordingly. As we know PI controller involves two separate variables: the Proportional and the Integral values. Where the proportional value determines the reaction to voltage error, and the Integral determines the reaction based on the sum of recent errors. The integral term added to the proportional term accelerates the movement of process towards reference voltage and eliminates the residual steady-state error that occurs with a P controller. The amplified error voltage so obtained is passed through Hysteresis control limiter which limits the value obtained by PID controller to certain value. By using pulse-width modulation (PWM) control regulation of output voltage is achieved by varying the duty cycle of the switches synchronously.

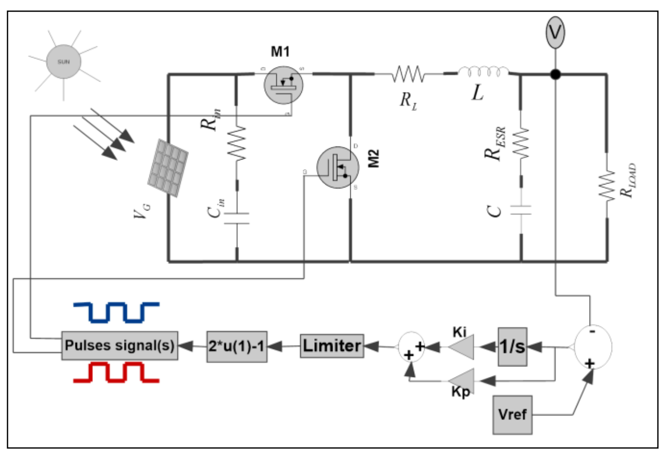

Fig.4.Schematic of closed loop control algorithm of Synchronous Buck Converter

Further, the frequency response of PI controller is plotted using Bode plot which is given in Fig.6. From Fig.6 we could observe that, the Gain Margin=15.9 db. With gain crossover frequency=7.62x103 rad.sec-1, and Phase Margin =88.8deg. With phase crossover frequency=582 rad.sec-1. Since phase crossover frequency is very less than gain crossover frequency, the controller reveals that, the system is highly stable.

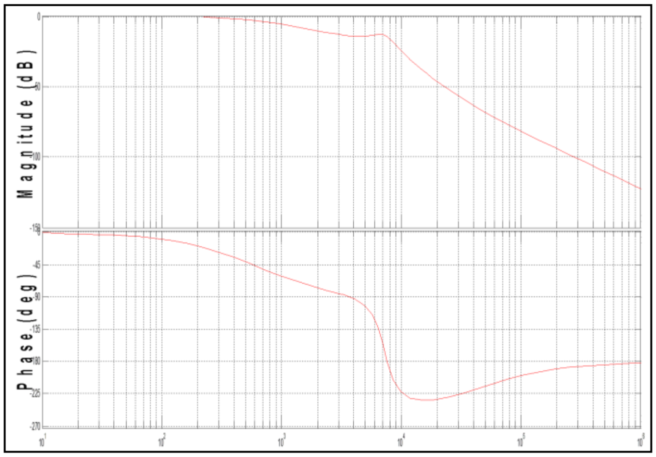

Fig.5.Bode plot of PI controller for Frequency Response.

SIMULATION RESULTS AND DISCUSSION

In order to verify the proposed study of small scale PV system of 19.8 W with dc-dc synchronous buck converter module of is modeled and tested in MATLAB/Simulink environment. The parameters taken for simulation study are given in the appendix. The performance of synchronous buck converter is analyzed under different operating conditions and the corresponding results are presented here.

During Step Changes in the Load:

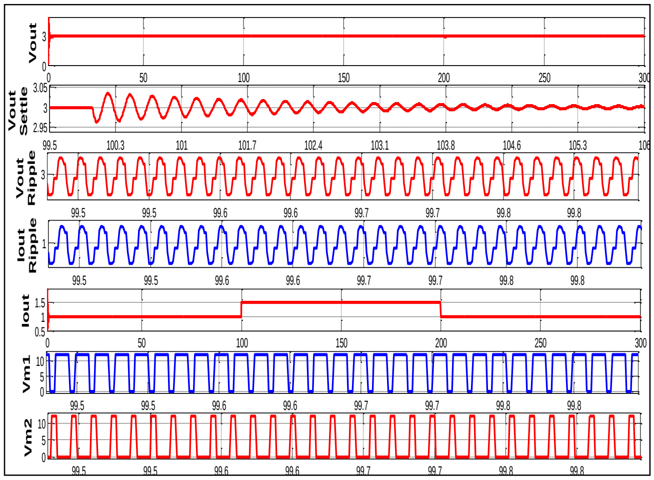

Fig. 8. Response of synchronous buck converter during step changes in the load. (a) Response of Output voltage (b) Settling of output voltage after change in load current. (c) output voltage ripple (d)output current ripple (e) Load Current (f) voltage stress across MOSFET "M1" (g) voltage stress across MOSFET "M2" .

Fig.8 depicts the dynamic response of Synchronous Buck Converter during step changes in the load. From Fig.2.2 (a), we could observe that, the output voltage settles less than 6ms and maintained constant irrespective of the load variation from 1A to 1.5A as illustrated in Fig.8(d) During load variations, the transients in output voltage persist and it settles within 5ms from the evidence of

Fig.8.(b). Voltage stress across MOSFET 'M1' & MOSFET 'M2'are illustrated Fig.7 (d) and Fig.7 (e) with limited values according to desired value. Fig.7 (f) shows the response of input voltage from PV system which maintains constant at 12V.

During Variation of Solar irradiation and Temperature (Source Variation):

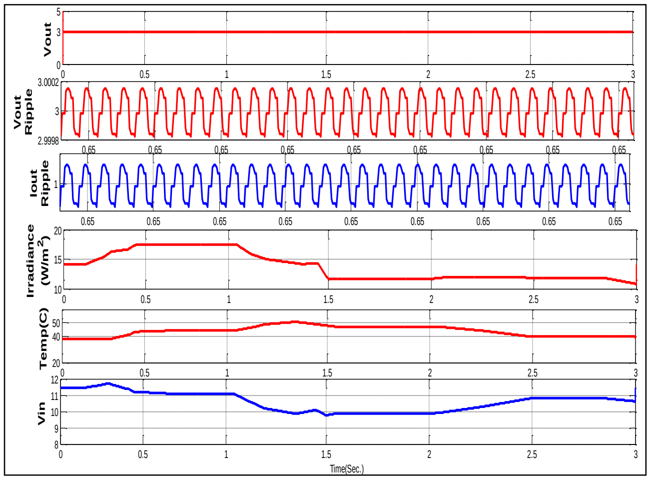

Fig. 9.Dynamics of Synchronous Buck Converter (a) ouput voltage (b) output voltage ripple (c)output current ripple (d)Solar Irradiation (f) Temperature (g)output voltage of PV-Array i.e. input to Synchronous Buck Converter.

As illustrated in Fig.9, the source variation is considered as PV is cell possessing highly non-linear characteristics between Ipv and Vpv due to variation of insolation and temperature. For more realistic study, solar irradiation and temperature is measured at NIT, Rourkela campus from 12 P.M to 3 P.M and are shown in Fig.9.(d) and Fig.9.(e) respectively. Due to variation on these parameters, Vpv is also getting varied and is depicted in Fig.9 (e). During this source variation, the controller can able to improve the dynamic response and it maintains the output voltage constant at 3 V and is shown in Fig.9 (a). Fig.9(b) & Fig.9(c) depicts that the output voltage ripple and output current ripple are limited to very less values by the help of high output capacitance.

Converter Design and Its Efficiency Calculation:

The following interpretations are made for capacitor and inductor calculation.

a) Inductance Calculation
For an inductor, $V=L*\Delta I/\Delta T$
Rearrange and substitute:
$L = (V_{in} - V_{out})*(D / F_{sw})/I_{ripple}$
b) Output Capacitor Calculation
For a capacitor, $\Delta V=\Delta I*(ESR+\Delta T/C + ESL/\Delta T)$
Assume ripple voltage of 50 mV
Then, $C_{out}= (\Delta I*\Delta T)/ (\Delta V-(\Delta I*ESR) =10.71\mu F$

The above obtained value of C_{out} is minimum value of output capacitance. To have the least amount of output ripple, capacitance can be increased to the desired value.

c) *Input Capacitor*

Input ripple current is assumed to be $I_{load}/2$

Acceptable input ripple voltage is 200 mV

Compute capacitance; C= ΔT / ((Vripple/ I_{ripple})-ESR) b

For better performance Input Capacitor value should be increased to a desired value.

d) *Synchronous Buck Converter Efficiency*

Output Power= 3 watts (3 V @ 1 a)

Inductor Loss=50mW $\{I_{load}^2 * ESR\}$

Output capacitor loss= 4.5mW $\{I_{ripple}^2 * ESR\}$

Input capacitor loss= 30 mW $\{I_{ripple}^2 * ESR\}$

Main MOSFET loss=105.52 mW

{[Conduction loss= $I_d^2 * R_{ds(on)} * D$]+[Switching loss= ($V_{diff} * I_d / 2)*(T_{on} + T_{off})*(F_{sw} + C_{oss} * V_{diff}^2 * F_{sw})$]}

Synchronous MOSFET loss Without Schottky Diode) = 107.7mW

{[Conduction loss= $I_d^2 * R_{ds(on)} * D$]+[Switching loss ($V_{diff} * I_d / 2)*(T_{on} + T_{off})*(F_{sw} + C_{oss} * V_{diff}^2 * F_{sw})$]}

Synchronous MOSFET loss(With Schottky Diode)=3.3mW

{[Conduction loss= $I_d^2 * R_{ds(on)} * D$]}

Total Loss (Without Schottky Diode) = 297.74 mW.

Converter efficiency (Without Schottky Diode) = 90.97 %

{(Pout/Pout+total losses)*100}

Total Loss (With Schottky Diode) = 193.32mW

Converter efficiency (With Schottky Diode) = 93.95 %

{(Pout/Pout+total losses)*100}

NOTE:

MOSFET M2 is clamped by a Schottky rectifier; it prevents the MOSFET's intrinsic body diode from conducting which prevents the body diode from developing a stored charge. The body diode in a MOSFET is a slow rectifier and would add significant losses if it were allowed to switch. Because the MOSFET rectifier (synchronous rectifier) switches with less than a volt across itself, the switching losses are almost zero. The MOSFET conduction losses are very low compared to the Schottky rectifier's forward voltage drop. Thus switching losses are reduced and efficiency is increased eventually. From the Fig.10, one can observe that, the efficiency of synchronous buck converter is more than that of conventional buck converter for same output power rating.

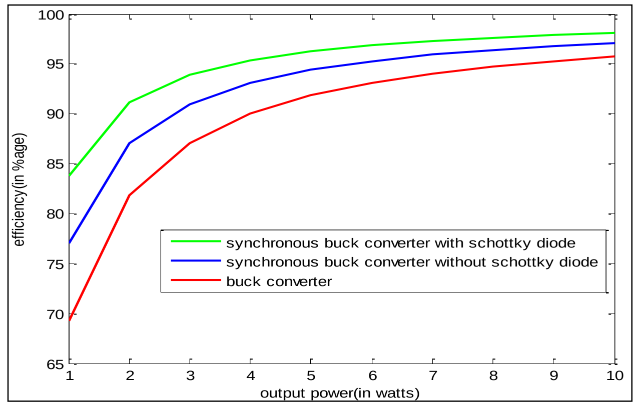

Fig.10. Converters' Efficiency comparison

CONCLUSIONS

In this paper, an accurate mathematical modeling and design of synchronous buck converter for low power PV energy system is presented. The core idea of paper is to use State Space Averaging technique for modeling of converter which decides precise values for PI controller used in control circuit. Synchronous buck converter with closed loop PI controller precisely improved the dynamic response of the system during load as well as source variation with reduced voltage and current ripple. Moreover, the circuit structure is simpler and much cheaper compared to other control mechanisms where large number of components is needed. Further, the converter design and its efficiency also determined. As results, the efficiency of synchronous buck converter is higher than conventional dc-dc buck converter for same power rating.

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